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ORI

WARC AND CCIR SUPPORT FOR SPECTRUM-ORBIT PLANNING

FINAL REPORT

PETER H. SAWITZ

30 MAY 1980

PREPARED UNDER CONTRACT NASW-3309 FOR HEADQUARTERS
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546

T. R. No. 1742

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Silver Spring, Maryland 20910

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INTRODUCTION

This report contains a large number of individual papers, all dealing with various aspects of spectrum-orbit utilization and with the effects on it of planning satellite services.

The purposes for which these papers were written fall into five classes: (1) information papers for the use of the U.S. delegation to the 1979 World Administration Radio Conference in Geneva, Switzerland; (2) contributions to the National CCIR Study Group 10/11B on Broadcasting Satellites; (3) contributions to the National CCIR Study Group IWP 4/1 on Spectrum-Orbit Utilization; (4) papers presented at technical conferences to broad engineering audiences; and (5) papers written in response to specific requests by certain groups or individuals.

The papers themselves are arranged in five appendices according to their purposes. In the following sections, brief summaries are given of the papers in each appendix.

SUMMARY OF APPENDIX A
INFORMATION PAPERS FOR THE U.S. DELEGATION

This appendix contains a paper prepared for the use of the U.S. delegation to the 1979 World Administrative Radio Conference in Geneva, Switzerland. This paper describes the results of a study of nonlinear optimization methods to be used in finding optimum positions of satellites in the fixed-satellite service. The main purpose of this study was to bring to the attention of the delegates the capabilities of modern computer programming techniques in solving spectrum-orbit utilization problems.

A second paper prepared for the use of the U.S. delegation dealt with the effects of geography on spectrum-orbit utilization. It is essentially the same as the contribution to CCIR Study Group 10/11B entitled "The Effects of Geography on the Use of the Geostationary Orbit" (Doc. USSG-BC/842) to be found in Appendix B, pg. B-3. It is therefore not included in this appendix. Its purpose was to demonstrate that there are many elements that are common to all kinds of planning, rigid as well as flexible, and that rigid planning is not necessary to achieve many of the purposes for which some type of planning seems indicated.

SUMMARY OF APPENDIX B
CONTRIBUTIONS TO CCIR STUDY GROUP 10/11B
(BROADCASTING SATELLITES)

This appendix contains seven papers contributed to the National CCIR Study Group 10/11B for submission to the 1980 Interim Meetings in Geneva, Switzerland. Of these, five were written entirely by ORI personnel: USSG BC/821, 842, 847, 849, and the unnumbered Modification of Study Programs 20C-2/10 and 5G-2/11. The other two papers, USSG BC/843 and 844, were edited by ORI personnel, and some contributions to them were made by ORI personnel, but they were mostly written by others.

Two of the papers, on the effects of geography on the use of the geostationary orbit and on the use of nonlinear programming for the optimization of satellite orbits, are draft new reports. The others are modifications of or additions to existing CCIR reports made necessary by the results of the 1979 WARC or by advancing technology.

SUMMARY OF APPENDIX C
CONTRIBUTIONS TO CCIR STUDY GROUP IWP 4/1
(SPECTRUM-ORBIT UTILIZATION)

This appendix contains four contributions to the National Study CCIR Study Group IWP 4/1. The first is a briefing given to the group on an ORI study entitled "Intercontinental Orbit Sharing," which explored the interactions between fixed satellite systems in the fixed-satellite service for North America on the one hand, and for South and Central America on the other. The second, Doc. USSG IWP 4/1-4, is a modified version of the report on the effects of geography on the use of the geostationary orbit contributed to CCIR Study Group 10/11B. While in the previous version the examples used were taken from the broadcasting-satellite service, here the emphasis is on applications to the fixed-satellite service. The third paper, Doc. USSG IWP 4/1-5, is a modified version of the report on the use of nonlinear programming for the optimization of satellite orbits. Here the emphasis is on the contribution that advanced programming techniques can make to increasing the efficiency of spectrum-orbit utilization, and applications are made to the fixed-satellite service. The last paper, Doc. USSG IWP 4/1-10, entitled "Traffic Coordination in Interfering Satellites Operating in the Fixed-Satellite Service," is another example of the use of special programming techniques to increase the capacity of the available resources.

SUMMARY OF APPENDIX D
PAPERS PRESENTED AT TECHNICAL CONFERENCES

This appendix contains two papers on very similar subjects. The first is entitled "The Effects of Geography on Spectrum-Orbit Utilization" and was presented at the National Telecommunications Conference in Washington, D.C., in November 1979. The second is a similar paper entitled "The Effects of Geography on Domestic Fixed and Broadcasting Satellite Systems in ITU Region 2." It differs from the first in that the emphasis is on domestic systems and the examples are taken from ITU Region 2, i.e., the Western Hemisphere. It was presented at the AIAA 8th Communications Satellite Systems Conference in Orlando, Florida, in April 1980.

SUMMARY OF APPENDIX E
RESPONSES TO SPECIFIC REQUESTS

This appendix contains responses to requests for technical analyses and evaluations.

The first paper is a memorandum for Dr. Akima. It is the response to a request made by the National Telecommunications and Information Agency (NTIA) to investigate a possible channel-orbit plan for the broadcasting-satellite service in the U.S. and Canada. The purpose of the investigation was to determine if a plan could be made to work that is based on the characteristics specified by the 1977 WARC-BS, and how many channels per service area could be provided under such a plan.

The second paper is a response to the original version of Doc. USSG BS/849, which was prepared by Dr. Akima. The response was prepared at the request of the chairman of CCIR Study Group 10/11B. It contains an analysis and evaluation of the technical points raised in the original document on the choice of polarization for broadcasting satellite systems.

The last paper is a response to Doc. USSG 4/3, prepared by Mr. Weinberger, on the communication capacity of the geostationary satellite orbit. It contains an evaluation of the document in terms of its suitability to further the U.S. objectives of promoting flexible approaches to planning and to support U.S. opposition to a priori frequency and orbital position allotment plans for the fixed-satellite service. The response was requested by the chairman of CCIR Study Group IWP 4/1.

APPENDIX A

INFORMATION PAPERS FOR
THE U.S. DELEGATION

APPICATION OF NONLINEAR OPTIMIZATION METHODS TO SATELLITE POSITIONING

TASK

ORI has investigated the application of non-linear optimization methods to the problem of geostationary satellite interference. The scope of the task includes:

- Development of the optimization algorithms
- Implementation of the algorithms into a computer program
- Check out of the program using a simple example with known results
- Comparison of the program results with the results published by Mizuno, Ito, Muratani, henceforth referred to as MIM
- Analysis of optimum satellite location for given satellites and various maximum interference levels
- Evaluation of optimization algorithms and program.

This report documents the results to date on this task.

MIM OPTIMIZATION TECHNIQUE

The optimization technique used follows the aggregate interference criteria for satellite spacing minimization developed in the paper by MIM. The MIM aggregate interference criteria for the i th satellite of an N satellite array is

$$\sum_{\substack{J=1 \\ J \neq i}}^{N} P_{ji} \, |\theta_i - \theta_j|^{-2.5} \leq P_i$$

where θ_i = longitude of i th satellite in degrees

P_i = maximum aggregate interference allowed for the i system in pWOp

P_{ji} = the interference from the j th satellite system on the i th satellite system in pWOp. P_{ji} is called the interference coeficient.

P_{ji} for 6/4 GHz systems is given by

$$P_{ji} = 9.185 \times 10^9 \, (Su_i \cdot Iu_j + 2.5 \cdot Sd_i \cdot Id_j) \quad (2)$$

where Su, Sd = up and down link interference sensitivities

Iu, Id = up and down link interference potentials.

This technique minimizes for a given satellite order the total satellite arc (i.e. $\theta_N - \theta_1$) for a total interference limit of P_i on each of the N satellites.

OPTIMIZATION FUNCTION AND CONSTRAINTS

The objective function to be minimized in the algorithm developed by ORI is

$$f = \theta_N - \theta_1$$

The constraints under which this minimization is performed are:

$$\sum_{\substack{j=1 \\ j\neq i}}^{N} P_{ji}\, \theta_{ji} \leq P_i, \quad i = 1 \text{ to } N$$

where $\theta_{ji} = |\theta_i - \theta_j|^{-2.5}$, for $(\theta_i - \theta_j)/(i-j) \geq 1$
$= (11 - 10\,(\theta_i - \theta_j)/(i-j))^2$, for $(\theta_i - \theta_j)/(j-i) \leq 1$

The reason for this form of θ_{ji} is to insure that the order of the satellites do not change during the processing. This is further explained in the next section.

OPTIMIZATION PROGRAM

The non-linear optimization program FLEXI developed by GSFC was used throughout this study. FLEXI is a flexible feasibility tolerance optimization program. It uses an unconstrained flexible polyhedron search technique. FLEXI can solve problems with linear or non-linear objective function and constraints and can use a feasible or non-feasible initial point. This algorithm is thoroughly described in Himmelblau (see references).

Because FLEXI permits non-feasible intermediate solutions it was found that during the processing the program would generate intermediate solutions that violated the satellite order constraints (i.e., $\theta_{i+1} \geq \theta_i$). As the program attempted to satisfy the satellite order constraints, it encountered the infinite interference barrier $(\theta_i - \theta_j)^{-2.5}$ at $\theta_i = \theta_j$ and could not return to the required satellite ordering. To solve this problem, a modification is made to the

interference constraint when a pair of satellites approach within 1 degree. The modified interference constraint is a steep monotonically increasing function of the violated satellite order. This new form for the interference constraint causes the quick detection and correction of satellite order changes. In addition, it relieves the necessity of satellite order constraints, thereby reducing program execution time by two-thirds.

PROGRAM CHECKOUT

The program was checked out with a simple non-linear problem and with one of the cases given in the MIM paper. The program gave correct answers for the simple non-linear problem for both interior solutions and boundary solutions whether the initial point was feasible or non-feasible.

Table 1 lists the satellite link parameters used for examples given in the MIM paper. Figure 1 shows the results MIM got for optimum satellite spacing for the ordering shown with a 1000 pWOp maximum aggregate interference constraint.

TABLE 1 LIST OF LINK PARAMETERS

Satel-lite	Iu [dBW/Hz]	Id [dBW/Hz]	Su [dB/K]	Sd [dB/K]
A	-46.6	-45.9	-25.6	-20.6
B	-35.0	-36.0	-23.8	-18.8
C	-41.0	-46.0	-31.9	-22.0
D	-30.0	-34.5	-33.3	-21.8
E	-45.0	-31.2	-10.2	-24.0
F	-45.6	-37.4	-14.4	-20.8
G	-35.5	-30.0	-16.2	-22.7
H	-37.0	-41.5	-24.3	-19.8
I	-43.4	-45.0	-19.8	-18.8
J	-31.0	-24.0	-12.1	-20.6

Uplink Interference Potential: $Iu = p_e$ [dBW/Hz]

Downlink Interference Potential: $Id = p_s g_s$ [dBW/Hz]

Uplink Interference Sensitivity: $Su = \frac{g_r \gamma}{T}$ [dB/K]

Downlink Interference Sensitivity: $Sd = \frac{1}{T}$ [dB/K]

p_e: Earth station transmit power density per Hz
p_s: Satellite transmit power density per Hz
g_s: Satellite transmit antenna gain
g_r: Satellite receive antenna gain
γ: Transmit gain of the interfered with satellite
T: Equivalent link noise temperature

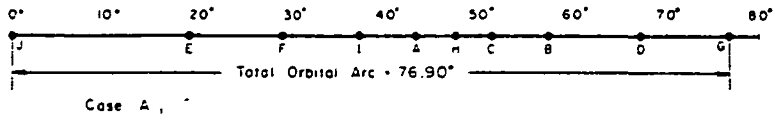

FIGURE 1 OPTIMUM SATELLITE SPACING FOR CASE A ORDERING

This case was duplicated using FLEXI. After 10 minutes execution time (on an Itel AS5 computer) FLEXI gave 77.3 degrees for the minimum orbital arc. The program had not converged, but appeared to be converging to very close to the 76.9 degrees reporting by MIM.

Table 2 lists the optimum satellite spacing generaged by FLEXI. This should be compared to Figure 1.

TABLE 1 OPTIMUM SATELLITE SPACING USING FLEXI

Satellite	Position (Degrees)
J	0.00
E	18.87
F	29.14
I	37.02
A	43.55
H	47.67
C	51.66
B	57.77
D	67.53
G	77.32

ANALYSIS OF INDIAN OCEAN SATELLITES

FLEXI was run to determine the optimum order and spacing of 4 Indian Ocean area satellites for maximum interference constraints of 1000 pWOp, 1500 pWOp, and 2000 pWOp for each satellite system. One modification was made to the interference coeficient for these runs. The 2.5 in equation 2 was replaced by 2.25. 2.5 is believed to be a typographical error. The factor should be the square of the ratio of up and down frequencies.

The satellites used in this analysis are listed with their link parameters in Table 3. Table 4 lists the minimum orbital arc for each of the

12 possible orderings of the 4 satellites for each maximum aggregate interference constraint. Table 5 lists the optimum satellite spacing for each order under the 1000 pWOp interference constraint. The numbers listed under "Order" in Tables 4 and 5 refer to the satellite number given in Table 3.

TABLE 3 SATELLITE LINK PARAMETERS

Satellite	Name	Iu	Id	Su	Sd
1	PALAPA	-30.0	-37.4	-12.6	-20.8
2	INSAT	-31.3	-28.0	-16.5	-24.1
3	INTELSAT	-32.8	-24.7	- 8.9	-18.9
4	STATIONAR 1	-30.0	-31.0	-20.0	-22.0

TABLE 4 MINIMUM TOTAL ORBITAL ARC

	Orbit Arc Length (Degrees)		
Order	1000 pWOp	1500 pWOp	2000 pWOp
1 2 3 4	63.75	54.21	48.31
1 2 4 3	46.84	39.83	35.50
1 3 2 4	59.75	50.80	45.28
1 3 4 2	60.19	51.18	45.62
1 4 2 3	46.27	39.34	35.07
1 4 3 2	63.62	54.10	48.21
2 1 3 4	64.65	54.97	49.00
2 1 4 3	56.20	47.79	42.59
3 1 2 4	49.50	42.09	37.51
3 1 4 2	49.33	41.94	37.38
4 1 2 3	55.78	47.42	42.27
4 1 3 2	64.12	54.52	48.59

TABLE 5 OPTIMUM SATELLITE SPACING AT 1000 pWOp
MAXIMUM INTERFERENCE

	Position			
	#1	#2	#3	#4
1 2 3 4	0.00	13.93	39.34	63.75
1 2 4 3	0.00	14.90	25.86	46.84
1 3 2 4	0.00	23.56	49.88	59.75
1 3 4 2	0.00	23.50	50.15	60.19
1 4 2 3	0.00	14.93	25.51	46.27
1 4 3 2	0.00	13.88	39.62	63.62
2 1 3 4	0.00	15.29	40.92	64.65
2 1 4 3	0.00	17.82	36.51	56.20
3 1 2 4	0.00	19.99	39.39	49.50
3 1 4 2	0.00	19.78	39.39	49.33
4 1 2 3	0.00	17.79	36.55	55.78
4 1 3 2	0.00	15.24	40.90	64.12

PROGRAM EVALUATION

FLEXI was evaluated for its ability to accurately, reliably, and quickly solve the problem of geostationary satellite interference. The results from FLEXI agreed well with previous results by MIM. In no case of the more than 25 cases analyzed, did the program appear to converge to a non-minimum solution.

All runs were made on an Itel AS5 computer. This is a fast computer, comparable to an IBM 370/168. The execution CPU time for the GO step varied significantly as a function of the number of satellites, the number and type of constraints, the convergence criterion, and the initial vector. In general, the CPU time increased rapidly with an increase in the number of satellites or the number of constraints.

Specifically, with 4 satellites, 0.1 degree convergence and 7 constraints, (4 interference limits and 3 order constraints), it took 23 seconds to converge; with 4 constraints and 1 equality constraint it took 40 seconds; with 4 constraints it took 8 seconds. With 4 constraints at 0.01 degree convergence and a different

initial vector it took 10 to 15 seconds to converge. However, with 8 satellites, 8 constraints and 0.01 degree convergence it took approximately 340 seconds to converge. Ten satellites and 10 constraints required over 600 seconds for convergence.

No attempt was made to modify the flexible polyhedron search parameters, which are (using Himmelblau's notation):

$$\alpha = 1.0$$
$$\beta = 0.5$$
$$\partial = 2.0$$

Himmelblau notes that gradient search methods using derivatives are faster than non-derivative search methods such as the flexible polyhedron used in FLEXI. The derivatives for the geostationary satellite problem are easily derived. Therefore a derivative type search method would be more efficient for this problem. No evaluation of computer programs other than FLEXI have been performed to date.

CONCLUSIONS

FLEXI programmed with ORI algorithm can be used to optimize geosynchronous satellite spacing for a given maximum interference level. No erroneous solutions were encountered during testing or use of the program. The results agree well with the results given in the paper by MIM.

The optimum order for the four Indian Ocean area satellites is PALAPA STATIONAR INSAT INTELSAT with an arc of 35.07 degrees at 2000 pWOp. Second best is PALAPA INSAT STATIONAR INTELSAT with 35.50 degrees at 2000 pWOp.

Using an Itel AS5 computer, FLEXI requires about 8 to 15 seconds CPU to converge to 0.01 degrees for 4 satellites. However, for 8 and 10 satellites the CPU time increases to over 5 minutes and 10 minutes respectively. An algorithm that used a derivative search optimization method would be faster.

REFERENCES

1. T. Mizuno, Y. Ito, T. Muratani; Efficient Use of Geostationary Satellite Orbit through Optimization of Satellite Locations, ICC '79.
2. D. Himmelblau; Applied Nonlinear Programming; McGraw-Hill, 1972.

APPENDIX B

CONTRIBUTION TO CCIR
STUDY GROUP 10/11B
(Broadcasting Satellites)

3-6-80
PHS

Addition to Report 631-1

In Section 5.2, add the following new paragraph before the last paragraph on the bottom of pg. 210 (Volume XI of 1978 Green Books):

The value of M_i, the margin for possible multiple interference entries, depends on the number and types of possible interferers. In the band under consideration (12.1 - 12.7 GHz), interference to the broadcasting-satellite service may be caused by other broadcasting-satellite transmitters, by satellite transmitters in the fixed-satellite service, and by transmitters in the fixed, mobile, and broadcasting services. Further work is required to determine how the total allowable interference should be allocated to the uplink, to other systems in the broadcasting-satellite service, and to other services that share the band with the broadcasting-satellite service.

Doc. USSG-BC/842
16 April 1980
Original: English

Received:

Subject: Study Programs 20C-2/10 and 5G-2/11

The United States of America

Draft New Report

THE EFFECTS OF GEOGRAPHY ON THE USE OF THE GEOSTATIONARY ORBIT

1. INTRODUCTION

This report discusses the effects of geographic features of service areas, such as size, shape, climate, and location, on the use of the geostationary orbit by broadcasting satellites. The information provided can be used in making estimates of the capacity of the spectrum-orbit resources under specific assumptions of system parameters and technological capabilities, and in making comparisons between different approaches to planning the broadcasting-satellite services.

Geographic features affect the use of the geostationary orbit by the broadcasting-satellite service in two ways: They completely determine the usable service arcs for the given service areas, and they interact in various degrees with the three techniques employed in the reuse of the same frequencies, namely orthogonal polarization, earth-station antenna discrimination, and satellite antenna discrimination.

This report first discusses the effects of geography on these items and obtains some general results. It then applies these results specifically to the broadcasting-satellite service in Region 2.

2. SERVICE ARCS

The service arc of an area is defined as that portion of the geostationary orbit from which useful service can be provided to any point in that area. It depends directly on the geographic features of latitude, size, and shape of the service area. It also depends on the minimum elevation angle required, which, in turn, depends on the geographic features of terrain (higher elevation angles are required in mountaneous terrain) and climate (higher elevation angles are required in areas with high rain rates). Finally, it depends on the requirements for eclipse protection. These requirements can impose severe restrictions on the service arc of an area (reducing it to somewhat less than half of what it would be otherwise), but are not connected with geographic features and therefore will not be discussed further here.

2.1 Effect of Latitude

For a single receiver located at a given point, and for an assumed minimum required elevation angle, the length of the service arc is a function of latitude only. Figure 1 shows the length of the service arc for such a point as a function of latitude for elevation angles from 0° to 40°. For an area that is narrow in latitude, so that all of its points are approximately at the same latitude, this length will be decreased by the distance (measured in degrees of longitude) between its easternmost and westernmost points. The curves of Figure 1 clearly show how the service arc decreases with latitude, slowly at first, and then with increasing rapidity at higher angles of latitude. They also show the severe restrictions on elevation angles at higher latitudes.

.2 Effects of Size and Shape

The service arc of an extended area of irregular shape is determined by the atitude and longitude of the two points in the area at which the elevation angle irst falls below the given value as the satellite moves east or west, respectively. hese points frequently are not obvious by inspection and must be determined by trial nd error or by graphical means.

In general, the larger the service area and the further north (in the northern emisphere) or south (in the southern hemisphere) it is, the smaller its service arc. or example, the 20° service arc of the 48 contiguous states of the US is about 32 legrees; that of Canada, which is somewhat bigger and, more importantly, extends much urther north, is zero because there is no possible satellite position on the geo-stationary arc from which all points of Canada can be seen at elevations of 20° or arger. At an elevation angle of 10°, the service arc of the 48 states is 75 degrees, vhile that of Canada is still zero. (If St. John's and Dawson are taken as the easternnost and westernmost points of the service area, and if the northernmost parts are excluded, the 10° service arc is 18 degrees.) Of course, the service arcs of individual time zones within either Canada or the United States, or even smaller subdivisions, are nuch larger. As another example of the effect of size, the 20° service arc of Brazil is about 83 degrees, while that of Paraguay, which is at about the same latitude but nuch smaller, is about 108 degrees.

As far as shape is concerned, a long narrow service area has a smaller service arc than a roughly circular one of the same size. For a service area near the equator, the east-west dimension tends to be the determining one; for a service area nearer one of the poles, the east-west dimension at the highest latitude is critical.

3. FREQUENCY REUSE

The key to efficient spectrum-orbit utilization is frequency reuse. If each frequency, or band of frequencies, were used only once, the capacity of the spectrum-orbit resource would simply be the total number of communication channels that can fit into the available bandwidth. The number of satellites would be irrelevant, as would be their positions and the distribution of service areas. There would be no interference, except perhaps between adjacent channels.

Frequency reuse is possible primarily through three techniques: orthogonal polarization, earth-station antenna discrimination, and satellite antenna discrimination. Geographic features have some effects on all three; but the one affected most is the satellite antenna discrimination. All three will be discussed below.

3.1 Orthogonal Polarization

The discrimination obtainable between two crosspolarized beams depends on two geographic features: the climate (which determines the rain statistics) and the location, i.e., the latitude and longitude, of the earth receiving station. Depolarization caused by rain is an important effect both with linear and with circular polarization. The variation of the received polarization angle with latitude and longitude, which may or may not be significant depending on several factors, will be present only with linear polarization. Both these effects are discussed in detail in CCIR Report 814.

3.2 Earth-Station Antenna Discrimination

The effect of geography on the earth-station antenna discrimination is a minor one. It comes about because of the variation of the ratio of topocentric to geocentric angles with latitude and relative longitude. For a given spacing between two satellites, expressed as the geocentric angle between them, the earth-station antenna discrimination will vary because it depends on the topocentric angle between the two satellites. The ratio of topocentric angle to geocentric angle varies from a maximum of 1.18 at locations near the subsatellite point and for geocentric angles of less than about 15° to a minimum of 0.99 at locations near the edges of the field of view or for geocentric angles near 90°. For latitudes of about 40° and for small angles of relative longitude and small geocentric angles it is close to 1.1. While these variations are small, they may be significant because, in some portions of the earth-station antenna pattern, the discrimination varies rather rapidly with off-axis angle.

3.3 Satellite Antenna Discrimination

The discrimination obtainable from the satellite antenna, according to the pattern adopted by the Broadcasting Satellite Conference (Geneva, 1977), is at most equal to its on-axis gain which, for the smallest beam width considered by that conference (0.6°), is 48.9 dB. This value is reached when the receiver is about 18 beamwidths away from the beam center. However, substantial values of discrimination are obtained at points much closer. The adopted pattern has a plateau that gives discrimination of 30 dB at points that are between 1.6 and 3.2 beamwidths away from beam center. Even larger values of discrimination are possible when shaped beams are used instead of the simple pattern adopted by the Conference. Thus, the relative location of different service areas, which determines their separation and therefore the amount of satellite antenna discrimination achievable, is the most important single geographic factor affecting spectrum-orbit utilization.

To show this in more detail, the separation angles required between pairs of satellites of four different systems have been computed for coincident service areas and for service areas separated by 1.6 bandwidths. To compute these angles, it was assumed that the relevant parameters of the four systems are those listed in Table 1; that the frequency is 12 GHz; that the BSS earth-station receiving antennas have the characteristics adopted by the 77 WARC-BS for Region 2; that the required protection ratio is 35 dB for the BSS; and that the ratio of topocentric to geocentric angle is 1.1 in all cases. Furthermore, 0.2 degrees were added to all separation angles to account for a station-keeping tolerance of 0.1 degrees for satellites, and possible differences in center frequencies and bandwidths used by the various systems were ignored, i.e., it was assumed that all interfering power from one (and only one) system was received by the other. For a service-area separation of 1.6 beamwidths, the discrimination was taken to be 27 dB, the difference between the 30 dB discrimination from the satellite antenna and the 3 dB gain reduction of a receiver at the edge of its service area. The resulting separation angles are listed in Table 2. It is seen that the effect of area separation is dramatic.

For adjacent service areas, the beam coverages usually overlap. In that case, the satellite antenna discrimination may be negative at some points. For then it is possible for a receiver that is located at or near the edge of its own service area to be on a higher gain contour of the interfering beam than of its own. Then the values of the required satellite separation angles may be substantially larger than those listed in Table 2 for coincident service areas.

To convey an idea of typical beam sizes and beam separations, Figure 2 shows a map of the Western Hemisphere as it would appear to an observer in the geostationary

TABLE 1

TYPICAL SYSTEM PARAMETERS

System		Antenna Diameter m	Satellite EIRP, dBw
1	Individual Reception	1.0	62
2	Community Reception	1.8	56
3	Community Reception	2.4	52
4	Community Reception	3.2	48

TABLE 2

SATELLITE SPACING REQUIRED (DEGREES)

Interfering Systems	Separation of Service Areas	
	Coincident	1.6 Beamwidths
1 and 1	19.0	1.7
1 and 2	15.3	1.5
1 and 3	16.6	1.6
1 and 4	17.9	1.7
2 and 2	8.9	0.9
2 and 3	9.6	1.0
2 and 4	10.4	1.0
3 and 3	6.7	0.8
3 and 4	7.3	0.8
4 and 4	5.1	0.6

orbit. On it are shown circular beams of 2° and 0.6° widths together with the corresponding separation of 1.6 beamwidths.

3.4 Improvement by Using Shaped Beams

Shaped beam antennas are presently used in Intelsat IV-A, the Japanese Communication Satellite (CS) and Broadcasting Satellite for Experimental Purposes (BSE), and planned for Intelsat V, among others.

The performance achievable using shaped beam technology is illustrated by the results of a recent computer simulation. The service area chosen exhibited a very irregular boundary (long in one direction and relatively narrow in the other) as shown in Figure 3. A 2.5 meter offset reflector employing a 21-horn feed and operating at a frequency of 11 GHz are assumed. The computed gain contours to the -10 dB level are also shown in Figure 3. The computed co-polar antenna pattern along the a-a and b-b directions shown in Figure 3 is given in Figure 4. For purposes of comparison the equivalent CCIR antenna envelopes for beams with circular or elliptical cross-section are also shown.

It may be seen from Figure 4 that shaped beams may result in a substantial reduction in the off-axis angle at which a given discrimination is achieved. For example, the "WARC-77" curve associated with the b-b curve would, if extended, cross the -35 dB line at approximately 20.5°, whereas the corresponding shaped-beam curve achieves this same discrimination at about 2.7°. Thus, collocated satellites or closely spaced satellites can be used for many more service areas with shaped beams than would be possible using the patterns adopted by the 1977 WARC.

Shaped beam antenna patterns may be economically desirable because, by more efficient use of transponder power (decreasing wasteful spillover), the required transponder power for covering a service area can be reduced significantly. However, to produce a shaped beam generally requires a larger antenna than would be required otherwise. For example, the pattern of Figure 1 required a 2.5 m antenna, while the corresponding 77 WARC patterns could be produced with a 90 cm antenna. Further work is required to determine the net effect on spacecraft weight and cost.

4. SPECIAL FEATURES OF ITU REGION 2

4.1 Boundaries

Region 2 differs from the other two regions in that its boundaries both on the east and on the west are almost entirely over water. And, with two exceptions - Iceland and eastern Siberia -, there are no significant inhabited land masses outside the boundaries and close to them. Furthermore, both the eastern and the western boundaries generally run in a north-south direction.

These features have two important consequences. Firstly, they generally reduce the interactions between broadcasting-satellite services in Region 2 and those in Regions 1 and 3. If the gain patterns adopted by the 1977 Conference are assumed, and if the criterion of a separation of 1.6 beamwidths (where a discrimination of 30 dB is reached) is used, then there are only three areas in Region 2 which can have significant interference problems with areas in Region 1 or 3: Alaska and eastern Siberia; Greenland and Iceland; and eastern Brazil and western Africa.

Secondly, the service arcs of the countries of Region 2 have little overlap with those of the countries of Regions 1 and 3, the notable exception being the arc

from about 0° to 40° west longitude, which is useful for many countries both in South America, and in Africa and Europe. In fact, this potential conflict was explicitly recognized by the 1977 Conference and resulted in some special provisions of its Final Acts. But apart from that conflict, satellites serving areas in Region 2 can be placed almost independently of the broadcasting-satellite systems serving Regions 1 and 3.

4.2 Division into Subregions

A look at the map of Region 2 reveals the obvious division into three subregions, also recognized by common nomenclature: South America, Central America, and North America. Greenland, which is part of Region 2, is not formally part of North America, but geographically it is an appendage thereof.

One important consequence of this division is the relatively weak interaction between North America and South America. Their exact separation in terms of beamwidths depends, of course, on the size of the service areas chosen, particularly in the larger countries that are likely to be covered by more than one service area, such as Brazil, the US, and Canada. But for most of the likely choices (eight or more service areas in Brazil, the US, and Canada; one service area for each of the other countries), the only service areas of North and South America that are not separated from each other by at least 1.6 beamwidths are Mexico in the north and Columbia and Venezuela in the south.

On the other hand, there are strong interactions between Central America (which is taken here to include the Caribbean islands) and North America, and between Central America and South America.

Another feature of the division into subregions is the fact that most of South America lies entirely to the east of most of Central and North America. While the east-west separation between South America and the rest of Region 2 is not as pronounced as the north-south separation, it does lead to the fact that a substantial portion of the orbital arc (east of about 40° west longitude) is useful for South America but not for North America. However, considerations of eclipse protection will make the eastern portion of their service arcs less attractive to the countries of South America. All of this is made less important by the fact that all countries of South and Central America have comparatively large service arcs. This comes about because almost all of them, excepting only Argentina, Chile, and Uruguay, lie between the latitudes of -30° and +30°, and most of them (all of them in Central America) are comparatively small.

4.3 Consequences

As a consequence of these features, planning the broadcasting-satellite services for North and South America can proceed relatively independently. But planning for Central America must be closely coordinated with both North America and South America, and vice versa.

Two satellites providing broadcasting services for individual reception to areas in North and South America, respectively, can be collocated if the service areas are separated by about five beamwidths or more. For a reasonable choice of service areas (at least eight each for Brazil, the US, and Canada, at least two each for Chile and Argentina), only a few South American areas (southern Chile and southern Argentina) are separated sufficiently from all of the US and Canada to allow collocated satellites. Some Canadian service areas could be paired with several South American ones for collocation of satellites. But it is unlikely that there will be satellites

oviding services exclusively to these northernmost regions without having also beams vering more southern areas. On the other hand, practically all of the South American rvice areas are separated sufficiently from the US and Canada to allow satellite spacgs as close as 1.7°. Considering the satellite spacings of 6° adopted by the 1977 nference for the Plan of Regions 1 and 3, and considering that the minimum spacing reired for satellites serving the same service area is 18.8° and for satellites serving eas separated by one beamwidth is 9°, it is clear that spacings of less than 4° will not useful for broadcasting satellites in any one subregion. This is true even if some ministration decides to implement broadcasting-satellite services for community recepon since the minimum spacing required in that case, with 1.8 m receiving antennas, is 9°. Thus, even though collocation of satellites will be possible only in a few exceponal cases, broadcasting satellites serving North and South America can generally be iterspersed without compromising the freedom of planning for either region.

It must be emphasized that the specific results given are based on the antenna itterns adopted by the 1977 Conference. The use of shaped beams and sidelobe reduction echniques would increase the relative independence of the regions and extend the appliibility of the results to many portions of Central America.

.4 Distribution of Countries

The North American portion of Region 2 contains only four countries: Mexico, the ;, Canada, and Greenland. Of these, the US naturally divides into three parts: the coniguous 48 states, Hawaii, and Alaska. Hawaii is naturally isolated from the other serve areas and need not be considered here. Alaska, Canada, and Greenland all have very nall service arcs because of their high latitudes. Thus, there is little flexibility in oosing satellite positions for broadcasting services to these countries.

South America contains thirteen countries, none of which has a 20° service arc f less than 47°, and only three of which (Argentina and Chile because of their latitudes, nd Brazil because of its size) have 20° service arcs of less than 108°. Central America ontains seven countries, and together with the Caribbean islands they form the potential or about 20 service areas or more, all of them comparatively small. None of them has a)° service arc of less than 112°.

Most of the South American and all of the Central American countries are in rain one 1, and therefore may require elevation angles as high as 40°. This will shrink neir service arcs, but will still leave most of them with service arcs of 66° or more.

. SUMMARY AND CONCLUSIONS

The geographic features of latitude, longitude, size, shape, terrain, and climate f a service area all determine the useful service arc for that area, and the locations f service areas relative to one another are the most important factors determining the ossibilities of frequency reuse.

The most important special feature of Region 2 is its natural division into ree subregions. Planning the broadcasting-satellite services in North and South nerica can be done in each of these subregions almost independently. Planning for entral America must be closely coordinated with the other two subregions. The coordiation is made simpler by the fact that all potential service areas in Central America e close to the equator and comparatively small, giving them comparatively large serve arcs.

As far as frequency reuse in different service areas is concerned, the side-obe level assumed for the satellite antenna is the most critical factor. The use of haped beams and sidelobe suppression techniques leads to significant increases in the ndependence of subregions.

KEY WORDS

Geography
Spectrum-orbit utilization
Satellites
Geostationary orbit

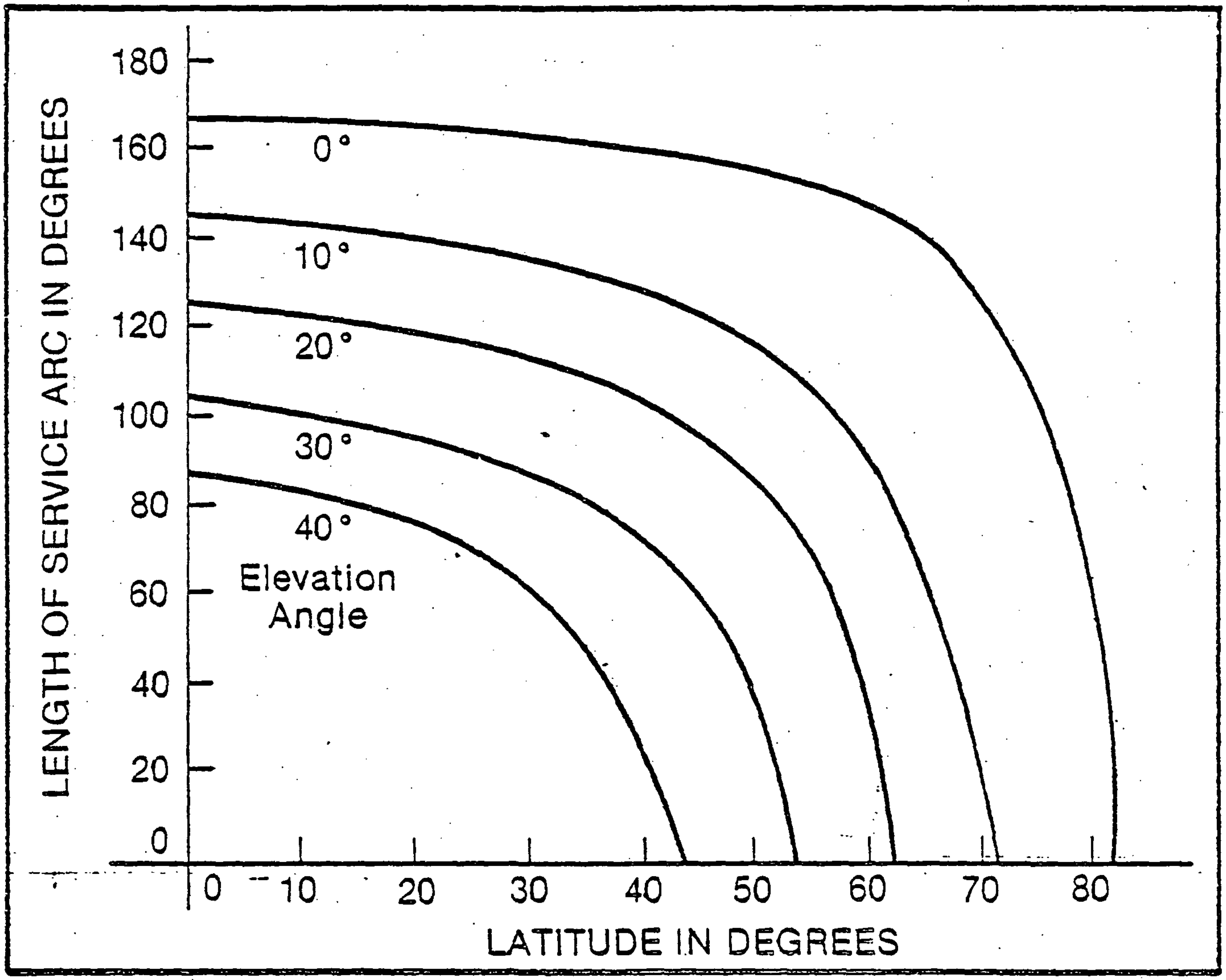

Figure 1. Service Arc of Single Receiver.

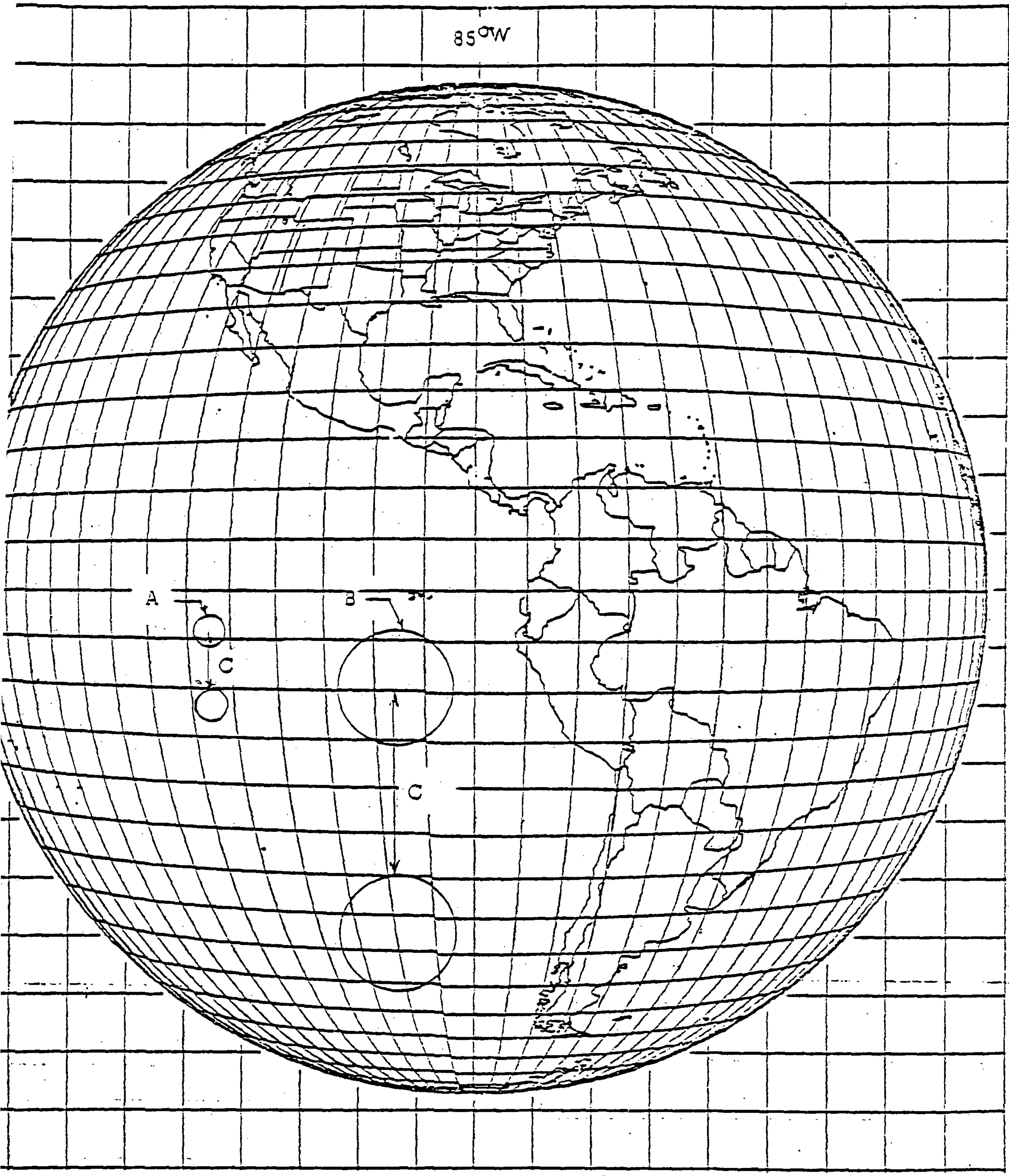

Figure 2. Typical Beam Sizes and Beam Separations

A: 0.6° beam
B: 2° beam
C: 1.6 beamwidths

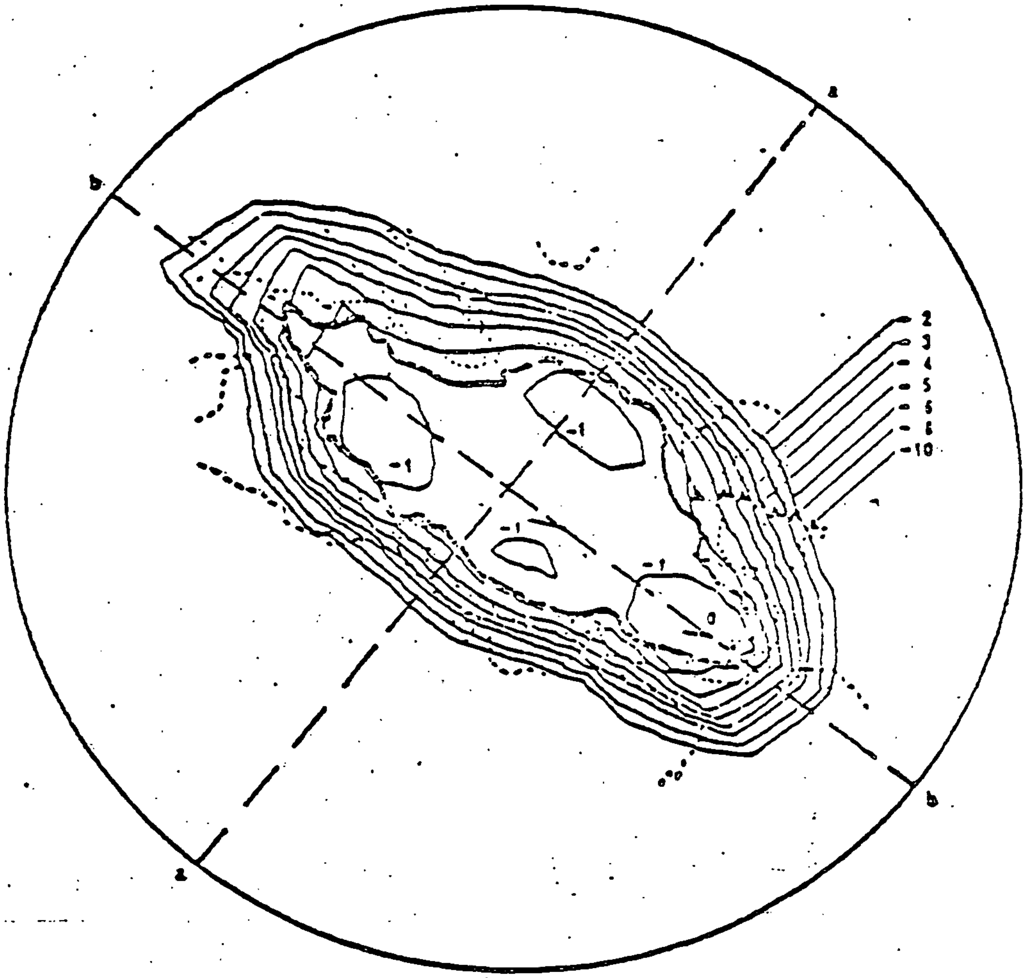

Figure 3. Computed Shaped Beam Pattern for a 21-Horn Parabolic Reflector System.

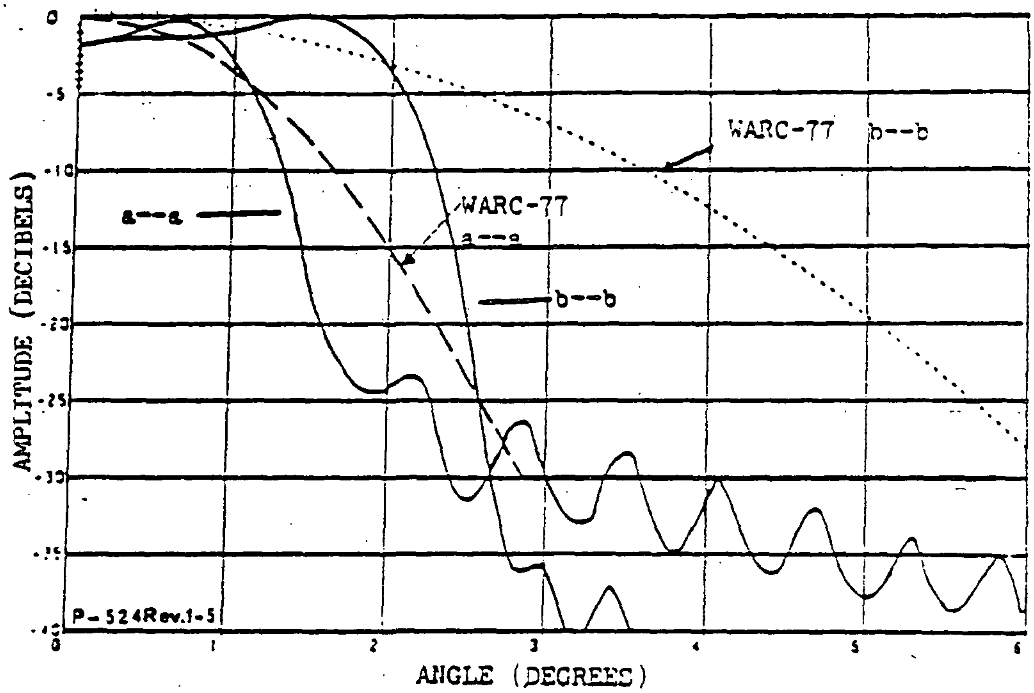

Figure 4. Computed Copoloar Antenna Beam Pattern.

· Documents
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riod 1978-1982

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16 April 1980
Original: English

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bject:

United States of America

MODIFICATIONS TO REP, 633-1

ORBIT AND FREQUENCY PLANNING IN THE BROADCASTING-SATELLITE SERVICE

:. 1. Mod. First paragraph.

, of a plan and its efficiency. ~~A-further-discussion-of-the-frequency-sharing-between-the oadcasting-satellite-service-and-the-fixed-satellite-service-can-be-found-in-Report-869~~.

rth paragraph.

"If it is proposed initially to operate a broadcasting-satellite service community reception and at a later date to operate broadcasting-satellite vices for individual reception in the same frequency band, both services uld employ the same modulation system ~~to-facilitate-compatibility~~ if an inistration wishes to facilitate compatibility between the earlier community the later individual reception system. Under such circumstances it would o be necessary to assume sharing criteria that would allow for the broadcasting ellite ultimately required. However, it may be possible, in some cases, to lement ~~two-or-more-community-broadcasting-satellites-within-the-spectrum-and it-assignment-made-to-one-individual-broadcasting-satellite-without-affecting plan,-i.e.-without-causing-unacceptable-interference-to,-or-receiving-unacceptable erference-from-systems-operating-in-accordance-with-the-plan.~~ more community adcasting satellites than individual broadcasting satellites. (based on the ater receiving antenna discrimination in the community system) in the same ital arc.

:. 2. Mod. Delete the third paragraph in its entirety.

.ete the fifth paragraph in its entirety and replace it by:

in some countries of Region 2, many systems in the fixed service are already operating in the 12 GHz band which they share with the broadcasting-satellite service. The possibility of reassigning frequencies to these terrestrial systems must be taken into account.

c. 3.2 Mod.

"...Where there will be a permanent requirement for community reception," e. with no intention for later conversion to individual reception.

:. 3.3 SUP. Delete this section in its entirety.

:. 3.4 Mod. Renumber this section 3.3.

:. 3. Mod. Add the following:

IMPACT ON PLANNING OF MULTI-SERVICE (HYBRID) AND MULTIBEAM SATELLITES

. INTRODUCTION

It is technically feasible, and in some cases may be economically esirable to use a single space station to provide two or more services such as SS, FSS and MSS (a "hybrid" satellite). It is also feasible to provide one or ore of these services to more than one administration using multiple beams (as iscussed in Sec. 3.1.4 of Rep. 11/475), or by time-sharing steerable beams, and ay be economically desirable to do so particularly in the case of those adminis-rations which have modest communications requirements for a limited time period. or example, this may be the case where services are just developing and have not et reached their full potential requirement which might ultimately require a fully edicated space station for each service or administration.

Certain studies (see references) have suggested that such multiple ervice/multiple beam systems may be particularly attractive economically given the rowing capability to launch large space platforms, although more conventional space tations can also be efficiently used to provide such services where total power equirements are modest.

However, such space station applications have important implications for rbit spectrum use and for planning in the utilized bands.

. MULTIPLE SERVICE SHARING

Report 809 and SPM 5.3.1.3 note that for some administrations in Region 2 t may be desirable, for economic reasons, to use the same space station for both he BSS and the FSS. By extension, a variety of other space services could also be ccommodated on a single space station using a variety of frequency bands /Edelson nd Morgan 77, Fordyce and Stamminger, 79/ and may lead to economic savings in roviding such services. For example, a single administration with presently odest requirements for any single service, may wish to use a single space station o provide BSS, FSS and MSS simultaneously, and in some cases to use the same arth stations for some or all of the services.

. ADMINISTRATIONS SHARING A MULTIPLE OR STEERABLE BEAM SATELLITE

The Region 1 and 3 plan of WARC shows that the same orbital position can e used to serve two or more administrations. This could be accomplished by using single space station of conventional type but with multiple beams where total ower requirements are modest, or by a larger space platform where total power equirements are large.

Total power requirements would depend on whether the concerned lministrations desired to implement, at any given time, the full number of annels available to them and/or the full transponder power allowed by a an or other regulatory limitation. For example, an interim service scheme is onceivable in which less than full capacity and/or power would be used, at ne choice of the concerned administrations, for a period of time (e.g. the fe of the satellite) until the full service was implemented at a later date.

Several administrations, allotted different orbital positions on the basis of their ultimate requirements, may for interim or developmental service wish to share the same space station with one or more channels assigned to each administration.

Report 665 notes that space station antennas can be steered or directed using arrays. Mechanically steered antennas operating over wide areas have been demonstrated on ATS-6 and CTS spacecraft. Thus, it is possible to time share a given satellite capacity, including individual transponders, among two or more administrations, although the foot print of the antenna will generally change when redirected, resulting in less than optimal coverage for differently shaped administrations. However, the same techniques used for beam shaping might also be used to reshape the beam for the different coverage areas.

Where two or more administrations time share the same channel, they would be using the same frequencies which may not be the frequencies allotted to each of them in a plan.

4. UPLINK CONSIDERATIONS

SPM 5.1.3.3.1.6 notes that the use of the same uplink frequencies for FSS and BSS at the same or nearby orbital positions (and thus for the same space station) is not possible in some cases. By extension this would be true for uplinks to any of the space services which could be accommodated on a single space station. Thus, for a single space station, separate frequency bands, or portions of bands, would be required for each downlink service. Where multiple administrations are served, different specific frequencies may be necessary for each administration or service area, depending upon such factors as antenna discrimination, beamwidth, separation of service areas, interference objectives, etc. Thus, uplink considerations in multi-beam or multi-service satellite, present important limitations.

5. IMPACT ON PLANNING

Plans which allot specific orbital positions and frequencies for one service will not in general be compatible with such plans for another service. Because of differing requirements and technical characteristics in different services, orbital allotments will not in general be the same for the different services in the same administration or service area. Thus, unless substantial flexibility were built into those plans, or plans were carefully coordinated with each other, multi-service satellites would not be possible to implement and the economic advantages of such satellites could not be achieved.

Plans which are based on long-term mature requirements of the participating administrations may not be compatible with economically attractive interim systems which could, using multi-beam or steerable time shared beams, serve the short or interim-term requirements of those same administrations. Once again, the economic advantages of such satellites could not be achieved and implementation of feasible services could be delayed.

The difficulties imposed by specific plans on the potentially technically and economically attractive shared use of space stations by different services or different administrations should be taken into consideration in planning the BSS in Region 2. The technical and economic benefits of shared use should be considered in conjunction with whatever benefits might accrue from the plan being analyzed. Flexibility in the implementation of a plan or bringing into service systems affected by a plan (such as stated as a principal for planning in Region 2 by Annex 6 to the final acts of 77 WARC (BS) could help to resolve some of the difficulties.

In particular, the opportunity to implement systems for interim service ı the near future while ultimate requirements are maturing, and while the orbit ›ectrum is not yet actively congested (and thus while maximally efficient orbit ›ectrum use is temporarily not of prime importance) could offer great benefits to lministrations while avoiding actual interference between services and administra-.ons.

Precise methods of taking multiple service/multiple beam space stations ıto consideration in planning have not been developed and require further study.

ıferences

Edelson and Morgan (Sept. 1977) Orbital Antenna Farms, Astronautics and Aeronautics.

Fordyce and Stamminger (1979) the Use of Geostationary Platforms for Future U.S. Domestic Satellite Communications. ICC'79 Proceedings, Vol. 3.

ɪc. 7.1 Mod.

First Paragraph.

"For planning purposes it ~~is convenient to assume~~ has in the past proved nvenient to assume..." "...and an alternative approach is to assume shaped ɪams in assessing the protection margin. In the shaped beam approach, modifications ı the following planning steps may be required. This requires further study."

ɪc. 10 Mod.

First Paragraph.

"Uplinks may affect planning of the broadcasting-satellite service for ~~vo~~ several reasons:..."

"...impose additional restrictions on the orbital positions of the roadcasting-satellites. (3) uplinks may require coordination with terrestrial or her systems with which they share the same frequency band (with attendant ɔntraints on planning) (4) it may be desirable that considerable numbers of small .xed or transportable uplinks operate from any point within the service area or ven in some cases, outside the service area, which may place constraints on the .anning process; (5) uplink bandwidth may be limited (see USSG BC/844) which may .ace constraints on the downlink plan. "A brief discussion..."

Second Paragraph.

Add at end: However, small fixed or transportable uplink Earth Stations ıy limit the directivity of earth station transmitting antenna or make it .fficult to employ more advantageous methods of modulation or polarization .scrimination.

Third Paragraph.

"~~For~~ If maximum flexibility in the positioning of satellites for direct roadcasting were required it ~~is~~ might be necessary to have the same or more total ındwidth allocated for uplinks than ~~as~~ for the downlinks (see SPM 5.2.9.3.4). .nce bandwidth is limited therefore, maximum flexibility may not be achievable.

Fifth Paragraph

"Thus an optimum situation should be sought in which, both in the plink and the downlink, orbital arc and frequency spectrum are used economically ithout unnecessary restrictions on the broadcasting channel plans, and in which e particular uplink requirements of individual administrations can be met ithout imposing unnecessary constraints on the downlink plans.

Thirteenth Paragraph.

"However, the planning of uplinks is especially important for interactive ystems or systems which require considerable numbers of small fixed or transportable plink earth stations. Interactive systems ~~in which~~ may require a very large number..."

"The problem of uplink frequencies for connection to broadcasting atellites is discussed in Rep. 811, 812 and 215-4 and is the subject..."

Key Words: Broadcasting satellite, planning, shaped beams, uplinks

Documents
CCIR Study Groups 10/11-B
Period 1978-1982

DOC. USSG BC/844
6 March 1980
Original: English

Received:

Subject:

United States of America

PLANNING ELEMENTS FOR THE BSS INCLUDING UPLINKS AND SHAPED BEAMS

(Modifications to Rep. 811)

Sec. 3.4 Sound Channel

"The question of supplementary sound channels has ~~not~~ been considered ~~in detail~~ in reports 632-1, 473-2, 488-2 and 215-4, but requires further study. Such sound channels could be used for stereo, or quadraphonic sound, multiple languages, audio programming not directly associated with the TV program and for digital information which could be used for a variety of purposes. In a television channel,..."

Add: 3.5 Interference Budget

For planning purposes, it is necessary to assume single-entry protection ratios for all possible sources of interference. These may include the uplink, other transmitters in the broadcasting-satellite service, and transmitters in other services with which the broadcasting-satellite service shares its frequency bands. Further work is required to determine how the total allowable interference should be allocated to these various sources.

Sec. 4.2 Copolar Reference Pattern of the Receiving Antenna

See Report ~~809~~ 810.

Sec. 4.3 Crosspolar Reference Pattern of the Receiving Antenna

See Report ~~809~~ 810.

Sec. 5.1 Antenna Beams

The SPM has reported on the improved orbit spectrum utilization and sharing with shaped beam antennas. (Sec. 5.2.8.1.2.3.4). See also Rep. 676 and 558-1.

"For planning purposes it ~~is~~ has in the past proved convenient to deal only with beams of elliptical, and as a special case, circular cross sections. However, more efficient plans may be possible if shaped beams could be incorporated into the planning process since, in the implementation..."

"The level of sidelobe supression that can be obtained with shaped beams requires further study. However, "shaped beams antennas are presently in use on INTELSAT IV-A, the Japanese communication satellite (ECS) and broadcasting satellite for experimental purposes (BSS) and planned for, among others INTELSAT V."

"The performance achievable using shaped beam technology is illustrated by the results of a recent computer simulation. The service area chosen exhibited a very irregular boundary (long in one direction and relatively narrow in the other as shown in Fig. 1. A 2.5 metre offset reflector employing a 21 horn feed and operating at a frequency of 11 GHz was assumed.

The computed gain contours to the patterns along the a-a and b-b directions shown in Fig. 1 are given in Figs. 2 and 3. For purposes of comparison, the equivalent CCIR antenna envelopes for beams with circular or elliptical cross-section are also shown.

Figure 4 shows an operational example of shaped beam coverage for PALAPA-B. This beam is achieved using a fixed parabolic reflector and multiple feed horns.

It should be noted that with shaped beams, peak PFD may not occur in the center of the beam, but close to the beam edge (as in the example here). Other beam shaping implementations could conceivable result in different patterns including ripple within the main beam. These considerations. along with rapid fall-off in the side lobes should be considered in defining the "coverage area" of a shaped beam.

It should also be noted that with shaped beams'rapid PFD fall-off outside the 3dB contour of the beam, changes in pitch, roll or yaw can have a more serious effect near the edge of the coverage area than with elliptical beams. This may require closer tolerances on antenna pointing, or coverage areas somewhat larger than service areas. Further study of the effects on these tolerances is required.

Sec. 5.9 Pointing Accuracy of the Antenna Beam

(Add at the end of the last paragraph:)

...for planning purposes. It should be noted that substantially smaller tolerances may be required, particularly for motion about the beam axis, if irregularly shaped antenna beams (see Section 5.1) are used.

6. Uplinks

6.1 System Considerations

"...For example the usefulness of some types of educational and health delivery services is greatly enhanced by the inclusion of a response capability. This possibility is mentioned in report (633-1) and needs further study."

ADD: Transportable and small fixed up-link earth stations providing direct connection to a broadcasting-satellite service for these and other purposes may be required in the near future and their numbers can be expected to increase as the broadcasting satellite service develops. An example of this application will arise in remote areas where terrestrial radio-relay systems are not available to the main earth station (from SPM 5.2.9.3.4).

ADD:

6.4 Bandwidth Requirements

(From SPM 5.2.9.3.4)

Recent studies undertaken by various Administrations in Regions 1 and 3 indicate that bandwidth in the range of 1 to 1.5 times the equivalent of the down-link allocation may be required. Some studies conclude that the equivalent to the down-link bandwidth could provide an adequate up-link service only if one or more constraints are introduced (the number of constraints depending on orbital position), such as:

- confining transmitting earth stations to the centres of the beams or at least ruling out the use of certain sites near the fringe of the service area;

- protection ratio for the up-link somewhat less than indicated in recommendation Sat-5 of Final Acts of WARC(BS)77;

- beamwidth of satellite receiving antenna smaller than the beamwidth of transmitting antenna in some critical areas;

- adjustments of EIRP of transmitting stations and deviation from the principle of a regular frequency translation in the satellite in some cases;

- up-link frequencies above 10 GHz.

In general relaxation of these constraints tends to lead to an increase in bandwidth requirement. On the other hand, restrictions, in particular for the location of earth stations, for EIRPs and for the receiving antenna beamwidth should in fact represent the elements of an up-link plan. However, it should be noted that restrictions on the earth station location for gaining frequency efficiency as discussed above would in certain cases impose severe constraints on the position of a transportable or multiple fixed earth stations.

Furthermore, transportable and some fixed earth stations as discussed in Sec. 6.1 will use relatively small antenna. However, if the antenna diameter becomes too small it will introduce excessive interference into adjacent satellites and could require even greater up-link bandwidth than discussed above. In general, it may be necessary to find the proper balance between earth station antenna diameter and satellite spacing.

The choice of frequency band would result in a reduction of bandwidth requirements at higher frequencies as a consequence of the narrower receiving beam. However, this places some restrictions on the location of earth stations, particularly in the case of multiple fixed and transportable earth stations. Further studies are required to determine if this advantage in bandwidth reduction could be reduced due to depolarization effects at the higher frequencies.

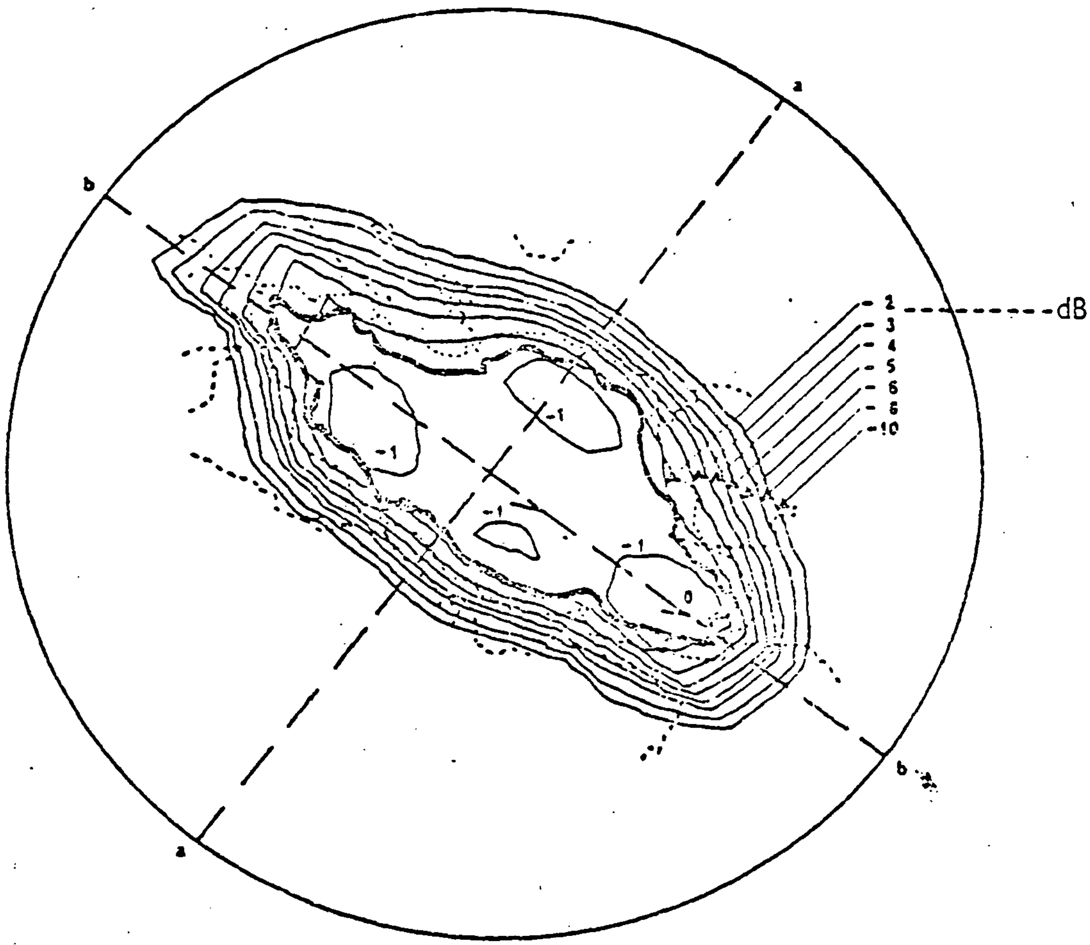


FIGURE 1

Computed shaped beam pattern at 11.379 GHz
for a 21-horn offset-fed parabolic reflector system

SPM Reference

5.2.8.1.2.3.4(a)

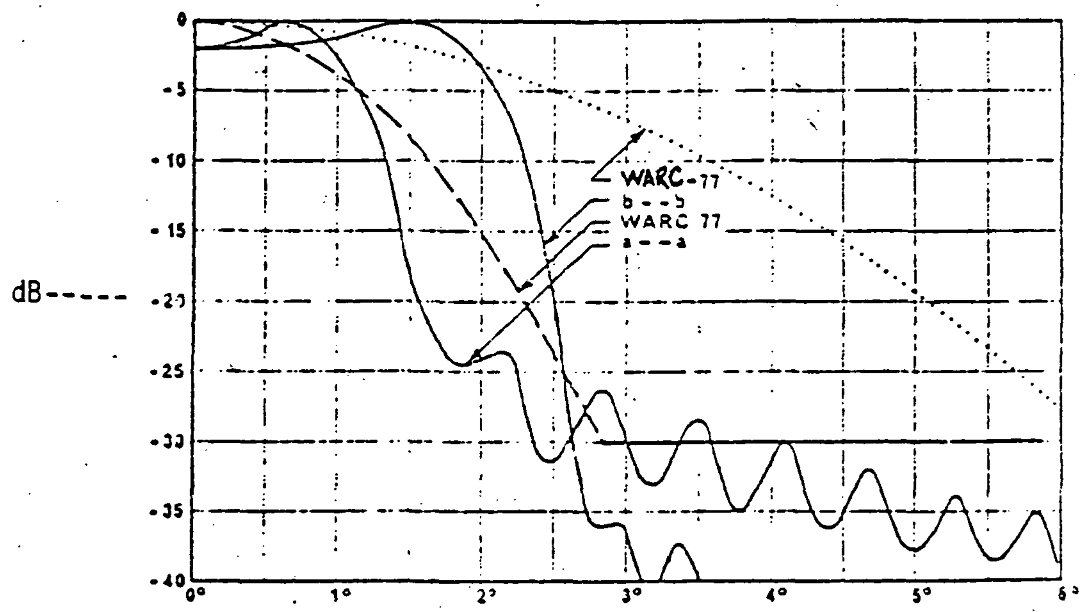


Figure 2

Computed co-polar antenna beam amplitude pattern

Curve b--b is compared to the dotted WARC-77 curve while a--a is compared o the dashed curve. The WARC curves are derived from Fig. 6 of Annex 8 of the 77 ARC BS final acts by using a Ø/Øo of 4° to convert from the dimensionless Ø/Øo urve to one in degrees.

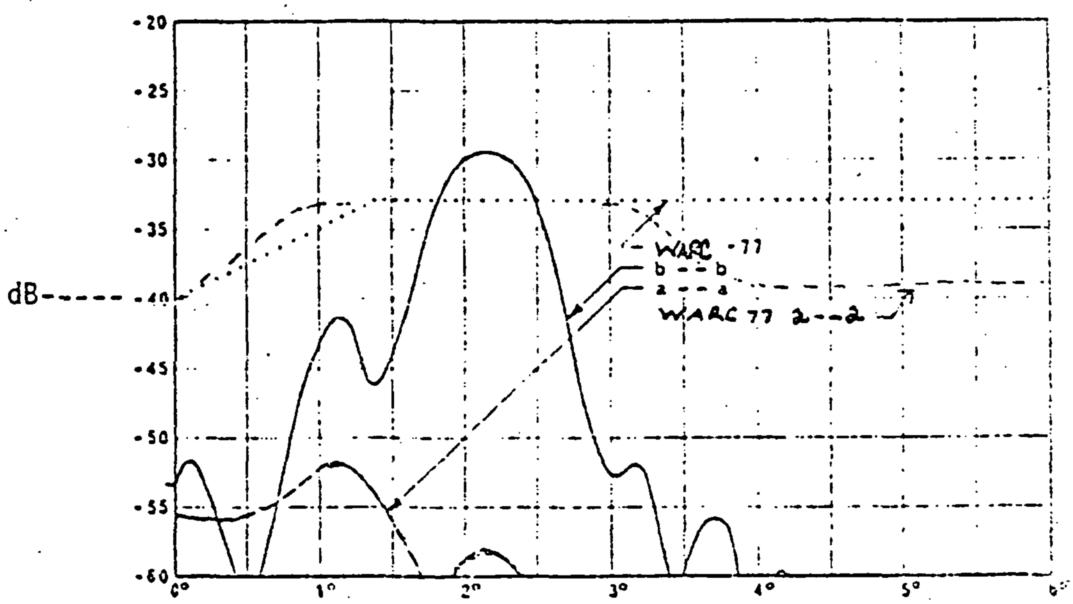
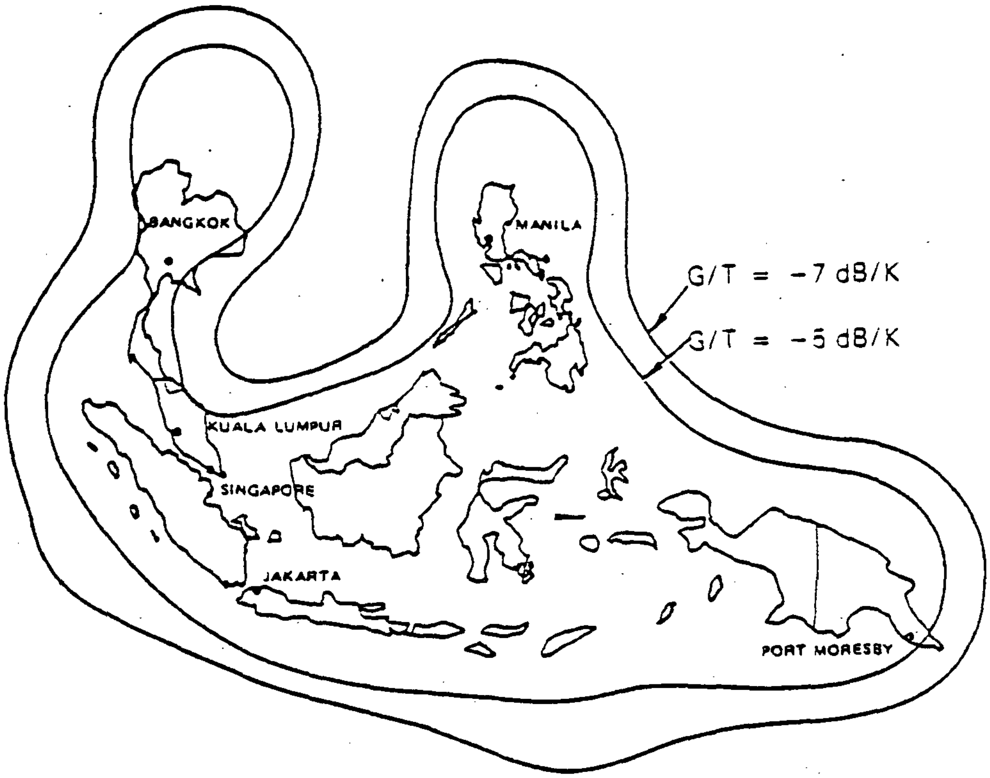


Figure 3

Computed cross-polar antenna beam amplitude pattern.

SPM reference 5.2.8.1.2.3.4 (b)



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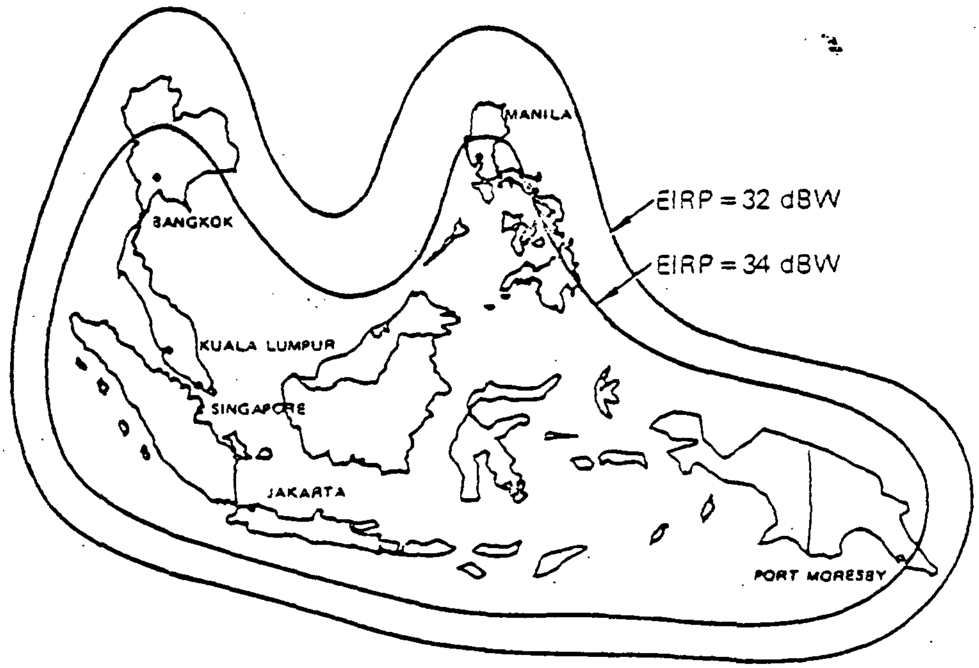

TRANSMIT

FIGURE 4 PALAPA-B COVERAGE

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R Study Groups
iod: 1978-1982

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16 April 1980
Original: English

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ject: Study Programs 20C-2/10 and 5G-2/11

THE UNITED STATES OF AMERICA

DRAFT NEW REPORT

USE OF NONLINEAR PROGRAMMING FOR THE
OPTIMIZATION OF SATELLITE ORBITS

INTRODUCTION

This paper describes the application of a nonlinear programming technique to the timization of the orbital positions of a set of non-homogeneous broadcasting satellites. total carrier-to-interference ratio at a receiver due to cochannel transmissions from all ier satellites determines the lower limit of the total orbital arc occupied. This techque could serve as a useful tool in planning a variety of services that require different tellite characteristics, e.g., for individual and for community reception.

NONLINEAR PROGRAMMING (NLP)

2.1 Nonlinear Programming Problem

The nonlinear programming problem can be stated as follows:

Find the set of independent variables, $\bar{x}$, that minimizes the objective function $f(\bar{x})$ subject to the m inequality constraints

$$g_i(\bar{x}) \geq 0, \qquad i = 1, \ldots, m$$

and n equality constraints

$$h_j(\bar{x}) = 0, \qquad j = 1, \ldots n.$$

e or more of f, g, or h is a nonlinear function of the independent variables $\bar{x}$. Any problem it can be expressed in this form is a nonlinear programming problem and, subject to certain itations, can be solved using nonlinear programming techniques.

2.2 Solution Procedure

Techniques to solve NLP problems use an iterative procedure to minimize the objece function. Given a solution $\bar{x}_k$ on the kth iteration, an improved solution $\bar{x}_{k+1}$ is ind by the following procedure:

(1) Determine search direction for the independent variables.

(2) Determine step length in this direction.

(3) Accomodate constraints.

(4) Test convergence.

this study a sequential unconstrained minimization technique (SUMT) was used to find the proved solution [1][2].

With SUMT, the constraints are introduced into the minimization procedure by adding a function of the constraints, the penalty function, to the objective function to form the modified objective function. The penalty function becomes positive when the constraints are violated, hence the term "penalty". When the constraints are met, the penalty function is zero or becomes zero as the search progresses.

The Davidson-Fletcher-Powell method [3] is used in this study to determine the search direction to decrease the modified objective function. Once the search direction is established the step length is determined by minimizing the modified objective function in this direction. Unidimentional minimization algorithms of Davis-Swann-Campy and Powell [2] are used. When the modified objective function has converged, the objective function is minimized under the given constraints.

3. APPLICATION TO BROADCASTING SATELLITE ORBIT OPTIMIZATION

3.1 Interference Constraints

To apply nonlinear optimization to broadcasting satellite orbit utilization, one must express the objective function and the satellite interference constraints in terms of the satellite positions. Assuming co-frequency satellites and broadcasting satellite antenna patterns specified in the Final Acts of World Administration Radio Conference on Broadcasting Satellites, the interference-to-carrier ratio in the i th system due to interference from the j th system is

$$N_{ji} = K_{ji} \quad \theta_{ij}^{-2.5}$$

where K_{ji} is the interference coefficient and

$$\theta_{ij} = \theta_i - \theta_j \qquad , \quad \theta_i - \theta_j \leq \theta_{i\,max}$$

$$\theta_{ij} = \theta_{i\,max} \qquad , \quad \theta_i - \theta_j > \theta_{i\,max}$$

θ_i is the relative longitude of the i th satellite. No distinction has been made between geocentric longitude and topocentric angle. At the latitude of the United States, topocentric angle is approximately 10 percent more than relative geocentric longitude.

If uplink power of 100 watts, and uplink EIRP of 76.3 dBW are assumed for all systems, the interference coefficient is

$K_{ji} = 3.72 \times 10^{-3} + F_j/(F_i\ D_i)$, where the first term is due to the uplink

F is the satellite EIRP in watts.

D is the downlink receiver gain descrimination factor, defined by $D = [G(0)/G(\phi)] \cdot \phi^{-2.5}$, where ϕ is the off-axis angle and G is the antenna gain.

The subscripts j and i refer to the interfering and interfered with systems respectively.

Using an aggregate interference-to-carrier ratio constraint

$$\sum_{\substack{j=1 \\ j\neq i}}^{n} N_{ji} = \sum_{\substack{j=1 \\ j\neq i}}^{n} K_{ji} \cdot \theta_{ij}^{-2.5} \qquad \leq N_i$$

3.2 Orbit Optimization

The optimum orbital positions of a set of geostationary broadcasting satellites is defined to be that order and those positions of the satellites that minimize the total arc of the set within the interference limit constraints. That is, minimize the objective function

$$f(\theta) = \theta_n - \theta_1$$

subject to the constraints

$$\sum_{\substack{j=1 \\ j\neq i}}^{n} N_{ji}(\theta_i, \theta_j) \leq N_i \quad , i = 1, \ldots n$$

During the SUMP optimization the total orbital arc of the satellites is progressively compressed until the interference constraints prevent the satellites from further approaching each other. The interference constraints also prevent the satellite order from changing during optimization. Therefore, the SUMT solution will converge to the satellite positions that yield the minimum arc for the given satellite order. Alternate satellite orders may need to be tested to find the smallest minimum arc.

4. EXAMPLE OF BROADCAST SATELLITE ORBIT OPTIMIZATION

4.1 Description

Nonlinear optimization was used to minimize the total orbital arc occupied by a set of nonhomogeneous broadcasting satellites. In this example, the earth-station antenna sizes were 1 meter for individual and 1.8, 2.4, and 3.2 meters for community reception. These are typical systems likely to be used in the Western Hemisphere. The first two antenna sizes were adopted by the 1977 World Administrative Radio Conference on Broadcasting Satellites. Table 1 lists typical values for the relevant characteristics of these systems. Total interference constraints of carrier-to-interference ratio (C/I) of 30 dB

TABLE 1

SYSTEM PARAMETERS

Type	Reception Type	Sate. EIRP (Kw.)	DRGD Factor*	θ_T max (degrees)
1	1-m. Individual	1580	7.1	27.3
2	1.8m Community	398	11.2	22.9
3	2.4m Community	158	23.0	21.6
4	3.2m Community	63.1	47.3	20.4

*Downlink receiver gain descrimination factor. (Defined in Section 3.1)

and 27 dB were used. Sets of four and seven satellites were analyzed. Table 2 lists the "best candidate" satellite position orders for orbital arc minimization. Satellite positions for each order were optimized by a computer program using the SUMT method. Optimum orbit results are given in Table 3.

TABLE 2

SATELLITE POSITION ORDERS

POSITION	SYSTEM TYPE				
	Four Satellites	Seven Satellites Case 1	Case 2	Case 3	Case 4
1	1	1	1	1	1
2	2	2	2	2	2
3	3	2	3	2	2
4	4	3	4	3	4
5		3	4	4	4
6		4	3	4	3
7		4	2	3	3

TABLE 3

MINIMUM TOTAL OCCUPIED ARCS (deg)

Interference Constraint	Four Satellites	Seven Satellites Case 1	Case 2	Case 3	Case 4
$C/I \geq 1000$	26.3	54.3	52.0	53.7	53.8
$C/I \geq 500$	19.7	39.2	37.6	38.7	39.1

4.2 Discussion of Results

Because satellite types 1 (1 m individual reception) and 2 (1.8 m community reception) produce the most interference, and satellite type 4 (3.2 m community reception) is most sensitive to interference, one would want to separate satellite type 4 from types 1 and 2. One would also expect that the adjacent placement of similar satellites would yield the best results. From these two assumptions, one would expect Case 1 to yield the minimum orbital arc. However, Table 3 shows that Case 1 yields the worst results of the four cases. Case 2, which separates type 4 from types 1 and 2 and also places type 2 at the end of the arc, where it has only one neighboring satellite, gives the best results. Note also that no decrease in interference is achieved by separating satellites more than θ_{i} max. Thus, it is not beneficial to separate satellite types 1 and 2 from type 4 by more than 20.4 degrees.

Table 4 shows the optimum satellite positioning for Case 2.

TABLE 4

OPTIMUM SATELLITE POSITION (CASE 2)

Position No.	Satellite Type	C/I ≥ 1000		C/I ≥ 500	
		Position (deg.)	Spacing (deg.)	Position (deg.)	Spacing (deg.)
1	1	0.0		0.0	
2	2	12.0	12.0	8.9	8.9
3	3	20.4	8.4	15.3	6.4
4	4	28.5	8.1	21.0	5.7
5	4	35.6	7.1	26.0	5.0
6	3	43.5	7.9	31.6	5.6
7	2	52.0	8.5	37.6	6.0

5. CONCLUSION

Nonlinear programming methods can be used to minimize the total orbital arc of a set of geostationary broadcasting satellites. To apply nonlinear programming, appropriate system interference constraints must be developed. The formulation of aggregate interference constraints for broadcasting satellites was presented here. Similar and/or alternate interference constraint forms can also be developed for other types of satellite antenna coverage [4] [5].

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KEY WORDS

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MODIFICATION OF REPORT 814

The following modification should be made in Annex 1 of Report 814, pg. 303 of volume XI of the Recommendations and Reports of the CCIR, 1978, in the definitions of the terms of the equation for θ_p:

θ_p: polarization angle of the incident wave relative to the local horizontal ~~plane~~ line, i. e., the line in the local horizontal plane that is perpendicular to the line from the satellite to the ground receiving terminal.

Reason: Correction of error.

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THE UNITED STATES OF AMERICA

Modification of Study Programs 20C-2/10 and 5G-2/11

1. In Study Program 20C-2/10 (BROADCASTING-SATELLITE SERVICE (SOUND), Use of the 12 GHz band) and in Study Program 5G-2/11 (BROADCASTING-SATELLITE SERVICE (TELEVISION), Use of the 12 GHz band), in the "UNANIMOUSLY DECIDES", add the following after the end of item 1:

2. determination for Region 2 of the technical characteristics of broadcasting-satellite systems which affect the utilization of the geostationary orbit, and their interrelationships;

3. determination for Region 2 of the techniques available to increase the efficiency of spectrum-orbit utilization for the broadcasting-satellite service in the 12 GHz band;

2. Renumber the remaining items 2 through 8 of the "UNANIMOUSLY DECIDES" so that they become items 4 through 10.

EXPLANATION

Wording similar to the added item 2 now appears in Study Program 2J-2/4: TECHNICAL FACTORS INFLUENCING THE EFFICIENCY OF USE OF THE GEOSTATIONARY-SATELLITE ORBIT BY RADIOCOMMUNICATION SATELLITE NETWORKS SHARING FREQUENCY BANDS ALLOCATED TO THE FIXED SATELLITE SERVICE. Since the broadcasting-satellite service no longer shares the entire band with the fixed-satellite service, it is necessary that the topic covered by this item becomes a part of a study program of Study Groups 10 and 11.

As to the added item 3, it is desirable that the techniques as well as the technical parameters become a subject of further study in view of item (e) of "CONSIDERING": that it is necessary to make the best possible use of the geostationary-satellite orbit and the frequency bands allocated to the broadcasting-satellite service.

APPENDIX C
CONTRIBUTIONS TO CCIR
STUDY GROUP IWP 4/1

BRIEFING

INTERCONTINENTAL ORBIT SHARING

PURPOSE

QUANTIFY INTERACTIONS BETWEEN FIXED SATELLITE SYSTEMS SERVING NORTH AMERICA ON THE ONE HAND, AND SERVING SOUTH AND CENTRAL AMERICA ON THE OTHER.

METHODOLOGY

DESIGN DETAILED PLAN FOR NORTH AMERICA (CANADA, US, AND MEXICO) WITH 4^{o} UNIFORM SPACING.

DESIGN DETAILED PLAN FOR SOUTH AND CENTRAL AMERICA (INCLUDING CARIBBEAN ISLANDS) (31 BEAMS) ALSO WITH 4^{o} UNIFORM SPACING, BUT OFFSET BY 2^{o} FROM THE NORTH AMERICAN PLAN.

FIND ORBIT CAPACITY FOR NORTH AMERICAN PLAN ALONE, THEN FOR SOUTH AND CENTRAL AMERICAN PLAN ALONE. FINALLY FIND CAPACITY FOR BOTH TOGETHER. DECREASE OF CAPACITY IS USED AS MEASURE OF INTERACTION.

THE MEASURE OF CAPACITY IS THE NUMBER OF VOICE CIRCUITS THAT CAN BE CARRIED IN A TRANSPONDER USING FDM/FM WITH NO MORE THAN 1500 PWPO OF INTERFERENCE POWER IN THE HIGHEST VOICE CIRCUIT.

ASSUMPTIONS

FREQUENCIES: C-BAND.

COCHANNEL INTERFERENCE ONLY, NO POLARIZATION DISCRIMINATION.

TRANSPONDER BANDWIDTH: 36 MHz, SPACING: 40 MHz. 12 TRANSPONDERS IN 500 MHz.

SYSTEMS ARE HOMOGENEOUS EXCEPT FOR BEAM SIZES.

ANTENNA SIZE: 10 M, SIDELOBE PATTERN: $32 - 25 \log \theta$.

SATELLITE ON-AXIS EIRP: 36 dBW.

UPLINK POWER FLUX DENSITY AT THE SATELLITE IS THE SAME FOR ALL BEAMS.

DETAILS OF PLANS

NORTH AMERICA: 22 SATELLITES, 66^{o} TO 150^{o} WEST LONGITUDE

SOUTH AND CENTRAL AMERICA: 23 SATELLITES, 40^{o} TO 128^{o} WEST LONGITUDE

NUMBER OF TRANSPONDERS ASSIGNED TO A COUNTRY IS PROPORTIONAL TO THE TOTAL NUMBERS OF TELEPHONES IN THAT COUNTRY, BUT NEVER LESS THAN 2.

TELEPHONES IN AND TRANSPONDERS FOR NORTH AMERICA

Country	Symbol	Number of Telephones (Millions)	Number of Telephones per Hundred Inhabitants	% of Total	Number of Transponders	
					By Formula	Assigned
USA	USA	154.6	71.8	89.9	234	204
Canada	CAN	13.8	60.4	8.0	21	36
Mexico	MEX	3.3	5.2	2.1	5	16
Total		171.7		100.0	260	256

TELEPHONES IN AND TRANSPONDERS FOR SOUTH AND CENTRAL AMERICA

Country	Symbol	Number of telephones (millions)	Number of telephones per hundred inhabitants	% of total	Number of transponders	
					by formula	assigned
Argentina	ARG	2.54	9.8	22.0	48	48
N. Anti.	ATN	0.048	19.9	0.4	2	2
Brazil	B	4.0	3.5	34.7	76	76
Bahamas	BAH	0.058	27.5	0.5	2	3
Bolivia	BOL	(0.25)	(5.0)	2.2	5	6
Barbados	BRB	0.044	17.8	0.4	2	3
Chile	CHL	0.47	4.5	4.1	9	12
Columbia	CLM	1.3	5.3	11.3	25	24
Costa Rica	CTR	0.127	6.2	1.1	3	3
Cuba	CUB	(0.43)	(5.0)	3.7	8	12
Dom. Rep.	DOM	0.17	2.6	1.1	3	4
Ecuador	EQA	0.174	2.5	1.5	3	4
Guadeloupe	GDL	0.027	7.9	0.2	2	3
Guatemala	GTM	(0.27)	(5.0)	0.2	2	6
Guyana	GUB	0.023	2.7	0.2	2	4
Fr. Guyana	GUF	0.009	17.8	0.1	2	4
Belize	HNB	0.006	4.3	0.0	2	2
Honduras	HND	0.020	0.7	0.2	2	2
Haiti	HTI	0.018	0.4	0.2	2	2
Jamaica	JMC	0.109	5.4	0.9	2	3
Martinique	MRT	0.035	10.2	0.3	2	2
Nicaragua	NCG	0.055	2.5	0.5	2	2
Panama	PNR	0.155	9.0	1.3	3	3
Paraguay	PRG	0.042	1.5	0.4	2	2
Peru	PRU	0.30	1.9	2.6	6	8
El Salvador	SLV	0.054	1.3	0.5	2	2
Surinam	SUR	0.019	4.9	0.2	2	4
Trinidad	TRD	0.070	6.6	0.6	2	3
Uruguay	URG	0.26	9.2	2.3	5	12
Venezuela	VEN	0.74	5.9	6.4	14	22
Virgin Is.	VIR	0.036	33.5	0.3	2	2
Total				100.0	244	284

SATELLITE POSITIONS FOR NORTH AMERICA

Satellite number	Satellite position deg. west longitude	Country served	Remarks
1	150	Mexico	
2	146	Mexico	
3	142	USA	Includes Alaska. Elevation angle: 10° at Washington, D. C.; 5° at Boston.
4	138	USA	Includes Alaska. Elevation angle: 10° at New York City; 5° in 50 states.
5	134	USA	Includes Alaska. Elevation angle: 10° at Boston; 7° in 50 states.
6	130	USA	50 states.
7	126	USA	48 states and Hawaii.
8	122	USA	48 states and Hawaii.
9	118	USA	48 states and Hawaii.
10	114	Canada	
11	110	Canada	
12	106	Canada	
13	102	USA	48 states.
14	98	USA	48 states.
15	94	USA	48 states.
16	90	USA	48 states.
17	86	USA	48 states.
18	82	USA	48 states.
19	78	USA	48 states.
20	74	USA	48 states.
21	70	USA	48 states.
22	66	USA	48 states.

SATELLITE POSITIONS FOR SOUTH AND CENTRAL AMERICA

Satellite number	Satellite position deg. west longitude	Countries served
1	146	Belize, Guatemala
2	128	Costa Rica, Honduras, Nicaragua, Panama, El Salvador
3	124	Peru, Ecuador
4	120	Venezuela, Netherland Antilles
5	116	Venezuela
6	112	Cuba
7	108	Columbia
8	104	Columbia
9	100	Argentina
10	96	Argentina
11	92	Barbados, Trinidad, Guadeloupe, Martinique, Virgin Is.
12	88	Argentina
13	84	Argentina
14	80	Bahamas, Jamaica, Dominican Republic, Haiti
15	76	Uruguay
16	72	Guyana, Surinam, French Guyana
17	68	Chile
18	64	Brazil
19	60	Brazil, Bolivia, Paraguay
20	56	Brazil
21	52	Brazil
22	48	Brazil
23	44	Brazil
24	40	Brazil

RESULTS

Beams	Number of Transp.	Number of Satel.	Capacity in 1000 v. chs.		Decrease %	
			30 dB	20 dB	30 dB	20 dB
North America alone	256	22	221	221		
North America combined	256	22	214	212	3.0	4.1
South and C. Am. alone	284	24	314	313		
South and C. Am. combined	284	24	294	288	6.5	8.1

	Number of transponders per million telephones
North America	1.49
South and Central America	23.9

CONCLUSIONS

NOTE: THE PLANS USED ARE NOT OPTIMUM.

1. THE OVERALL INTERACTION BETWEEN THE TWO PLANS IS WEAK. THE DECREASE IN CAPACITY FOR NORTH AMERICA IS 3% AT 30 dB OR 4.1% AT 20 dB, AND FOR SOUTH AND CENTRAL AMERICA IS 6.5% AT 30 dB OR 8.1% AT 20 dB.

2. THE INTERACTIONS IN CENTRAL AMERICA AND IN THE CARIBBEAN ISLANDS ARE MUCH STRONGER. THE DECREASE IS 53% IN THE BAHAMAS AND 40% IN EL SALVADOR. THE MAXIMUM DECREASE IN NORTH AMERICA IS 10%.

3. THERE IS LITTLE DIFFERENCE BETWEEN USING 20 dB AND 30 dB PLATEAUS. (LESS THAN 2%.)

4. THE SHAPED BEAMS SUPPLIED BY COMSAT GIVE SUBSTANTIAL IMPROVEMENTS. EXAMPLES:

LOCATION	IMPROVEMENT (dB)
EL SALVADOR	18.7
VENEZUELA	24.2
BAHAMAS (SOUTH)	11.1
BAHAMAS (NORTH)	0

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Draft New Report

THE EFFECTS OF GEOGRAPHY ON THE USE OF THE GEOSTATIONARY ORBIT

.. INTRODUCTION

This report discusses the effects of geographic features of service areas, such is size, shape, climate, and location, on the use of the geostationary orbit by satel-ites of the fixed-satellite service (FSS). The information provided can be used in naking estimates of the capacity of the spectrum-orbit resources under specific assump-:ions of system parameters and technological capabilities, and in making comparisons between different approaches to planning the space services.

Geographic features affect the use of the geostationary orbit by the FSS in two ways: They completely determine the usable service arcs for the given service areas, and they interact in various degrees with the three techniques employed in the reuse of the same frequencies, namely orthogonal polarization, earth-station antenna discrimination, and satellite antenna discrimination.

This report first discusses the effects of geography on these items and obtains some general results. It then applies these results specifically to the FSS in Region 2.

:. SERVICE ARCS

The service arc of an area is defined as that portion of the geostationary orbit from which useful service can be provided to any point in that area. It depends directly on the geographic features of latitude, size, and shape of the service area. It also depends on the minimum elevation angle required, which, in turn, depends on the geo-graphic features of terrain (higher elevation angles are required in mountaneous terrain) and climate (higher elevation angles are required in areas with high rain rates). Fi-nally, it depends on the requirements for eclipse protection. These requirements can impose severe restrictions on the service arc of an area (reducing it to somewhat less than half of what it would be otherwise), but are not connected with geographic fea-tures and therefore will not be discussed further here.

:.1 Effect of Latitude

For a single receiver located at a given point, and for an assumed minimum required elevation angle, the length of the service arc is a function of latitude only. Figure 1 shows the length of the service arc for such a point as a function of lati-tude for elevation angles from 0° to 40°. For an area that is narrow in latitude, so that all of its points are approximately at the same latitude, this length will be de-creased by the distance (measured in degrees of longitude) between its easternmost and westernmost points. The curves of Figure 1 clearly show how the service arc decreases with latitude, slowly at first, and then with increasing rapidity at higher angles of latitude. They also show the severe restrictions on elevation angles at higher latitudes.

:.2 Effects of Size and Shape

The service arc of an extended area of irregular shape is determined by the atitude and longitude of the two points in the area at which the elevation angle 'irst falls below the given value as the satellite moves east or west, respectively. 'hese points frequently are not obvious by inspection and must be determined by trial nd error or by graphical means.

In general, the larger the service area and the further north (in the northern emisphere) or south (in the southern hemisphere) it is, the smaller its service arc. 'or example, the 20° service arc of the 48 contiguous states of the US is about 32 egrees; that of Canada, which is somewhat bigger and, more importantly, extends much 'urther north, is zero because there is no possible satellite position on the geo- tationary arc from which all points of Canada can be seen at elevations of 20° or arger. At an elevation angle of 10°, the service arc of the 48 states is 75 degrees, hile that of Canada is still zero. (If St. John's and Dawson are taken as the eastern- ost and westernmost points of the service area, and if the northernmost parts are xcluded, the 10° service arc is 18 degrees.) As an example of the effect of size, the 0° service arc of Brazil is about 83 degrees, while that of Paraguay, which is at bout the same latitude but much smaller, is about 108 degrees.

As far as shape is concerned, a long narrow service area has a smaller service rc than a roughly circular one of the same size. For a service area near the equator, he east-west dimension tends to be the determining one; for a service area nearer one f the poles, the east-west dimension at the highest latitude is critical.

:. FREQUENCY REUSE

The key to efficient spectrum-orbit utilization is frequency reuse. If each 'requency, or band of frequencies, were used only once, the capacity of the spectrum- rbit resource would simply be the total number of communication channels that can fit nto the available bandwidth. The number of satellites would be irrelevant, as would e their positions and the distribution of service areas. There would be no inter- 'erence, except perhaps between adjacent channels.

Frequency reuse is possible primarily through three techniques: orthogonal olarization, earth-station antenna discrimination, and satellite antenna discrimina- ion. Geographic features have some effects on all three; but the one affected most is he satellite antenna discrimination. All three will be discussed below.

:.1 Orthogonal Polarization

The discrimination obtainable between two crosspolarized beams depends on two eographic features: the climate (which determines the rain statistics) and the loca- ion, i.e., the latitude and longitude, of the earth receiving station. Depolariza- ion caused by rain is an important effect both with linear and with circular olarization. The variation of the received polarization angle with latitude and ongitude, which may or may not be significant depending on several factors, will be resent only with linear polarization. Both these effects are discussed in detail in CIR Reports 555-1 and 814.

.2 Earth-Station Antenna Discrimination

The effect of geography on the earth-station antenna discrimination is a minor ne. It comes about because of the variation of the ratio of topocentric to geo-entric angles with latitude and relative longitude. For a given spacing between two atellites, expressed as the geocentric angle between them, the earth-station antenna iscrimination will vary because it depends on the topocentric angle between the two atellites. The ratio of topocentric angle to geocentric angle varies from a maximum f 1.18 at locations near the subsatellite point and for geocentric angles of less than bout 15^0 to a minimum of 0.99 at locations near the edges of the field of view or for eocentric angles near 90^0. For latitudes of about 40^0 and for small angles of rela-ive longitude and small geocentric angles it is close to 1.1. While these variations re small, they may be significant because, in some portions of the earth-station ntenna pattern, the discrimination varies rather rapidly with off-axis angle.

.3 Satellite Antenna Discrimination

The discrimination obtainable from the satellite antenna, according to the CCIR uggested reference pattern (Report 558-1), reaches 35 dB (a value frequently used as he required single-entry protection ratio) when the receiver is about 13 beamwidths way from beam center. As much as 20 dB of discrimination is achieved at points about .3 beamwidths away from beam center. The Broadcasting Satellite Conference (Geneva, 977), noting advances in antenna technology, adopted a satellite antenna pattern that as a gain plateau of 30 dB discrimination at points that are between 1.6 and 3.2 beam-idths away from beam center. Even larger values of discrimination are possible when haped beams are used instead of the simple pattern adopted by the Conference. Thus, the elative location of different service areas, which determines their separation and herefore the amount of satellite antenna discrimination achievable, is the most impor-ant single geographic factor affecting spectrum-orbit utilization.

As an illustration, at C-band the spacing required between satellites in the FSS hat serve identical areas is about 4^0 to 5^0, depending on system characteristics. If hese satellites serve areas that are separated by at least 1.6 beamwidths, the required pacing is reduced to less than 1^0.

For adjacent service areas, the beam coverages usually overlap. In that case, he satellite antenna discrimination may be negative at some points. For then it is ossible for a receiver that is located at or near the edge of its own service area to e on a higher gain contour of the interfering beam than of its own. Then the values f the required satellite separation angles may be substantially larger than those or coincident service areas.

.4 **Improvement by Using Shaped Beams**

Shaped beams are in common use today, for example in Intelsat IV-A and in both the Japanese communication Satellite and in the Japanese Broadcasting Satellite for Ex-perimental Purposes. They are planned for several future satellites, e.g. Intelsat V.

The performance achievable using shaped beam technology is illustrated by the results of a recent computer simulation. The service area chosen exhibited a very rregular boundary (long in one direction and relatively narrow in the other) as shown n Figure 2. A 2.5 meter offset reflector employing a 21-horn feed and operating at a frequency of 11 GHz are assumed. The computed gain contours to the -10 dB level are lso shown in Figure 2. The computed co-polar antenna pattern along the a-a and b-b directions shown in Figure 2 is given in Figure 3. For purposes of comparison the

equivalent CCIR antenna envelopes for beams with circular or elliptical cross-section are also shown.

It may be seen from Figure 3 that shaped beams may result in a substantial reduction in the off-axis angle at which a given discrimination is achieved. For example, the "WARC-77" curve associated with the b-b curve would, if extended, cross the -35 dB line at approximately 20.5^0, whereas the corresponding shaped-beam curve achieves this same discrimination at about 2.7^0. Thus, collocated satellites or closely spaced satellites can be used for many more service areas with shaped beams than would be possible using the patterns adopted by the 1977 WARC.

Shaped beam antenna patterns may be economically desirable because, by more efficient use of transponder power (decreasing wasteful spillover), the required transponder power for covering a service area can be reduced significantly. However, to produce a shaped beam generally requires a larger antenna than would be required otherwise. For example, the pattern of Figure 1 required a 2.5 m antenna, while the corresponding 77 WARC patterns could be produced with a 90 cm antenna. Further work is required to determine the net effect on spacecraft weight and cost.

4. SPECIAL FEATURES OF ITU REGION 2

As an example of the application of these principles, the following paragraphs describe the geographical features of ITU Region 2 that have significant effects on the use of the geostationary orbit.

4.1. Boundaries

Region 2 differs from the other two regions in that its boundaries both on the east and on the west are almost entirely over water. And, with two exceptions - Iceland and eastern Siberia -, there are no significant inhabited land masses outside the boundaries and close to them. Furthermore, both the eastern and the western boundaries generally run in a north-south direction.

These features have two important consequences. Firstly, they generally reduce the interactions between satellite systems in Region 2 and those in Regions 1 and 3. If the gain patterns adopted by the 1977 Conference are assumed, and if the criterion of a separation of 1.6 beamwidths (where a discrimination of 30 dB is reached) is used, then there are only three areas in Region 2 which can have significant interference problems with areas in Region 1 or 3: Alaska and eastern Siberia; Greenland and Iceland; and eastern Brazil and western Africa.

Secondly, the service arcs of the countries of Region 2 have little overlap with those of the countries of Regions 1 and 3, the notable exception being the arc from about 0^0 to 40^0 west longitude, which is useful for many countries both in South America, and in Africa and Europe. But apart from that conflict, satellites serving areas in Region 2 can be placed almost independently of the satellite systems serving Regions 1 and 3.

4.2 Division into Subregions

A look at the map of Region 2 reveals the obvious division into three subregions, also recognized by common nomenclature: South America, Central America, and North America. Greenland, which is part of Region 2, is not formally part of North America, but geographically it is an appendage thereof.

One important consequence of this division is the relatively weak interaction between North America and South America. Their exact separation in terms of beamwidths depends, of course, on the size of the service areas chosen, but if one assumes

one service area per country, the only service areas of North and South America that are not separated from each other by at least 1.6 beamwidths are Mexico in the north and Columbia and Venezuela in the south.

On the other hand, there are strong interactions between Central America (which is taken here to include the Caribbean islands) and North America, and between Central America and South America.

Another feature of the division into subregions is the fact that most of South America lies entirely to the east of most of Central and North America. While the east-west separation between South America and the rest of Region 2 is not as pronounced as the north-south separation, it does lead to the fact that a substantial portion of the orbital arc (east of about 40° west longitude) is useful for South America but not for North America. All of this is made less important by the fact that all countries of South and Central America have comparatively large service arcs. This comes about because almost all of them, excepting only Argentina, Chile, and Uruguay, lie between the latitudes of -30° and +30°, and most of them (all of them in Central America) are comparatively small.

4.3 Distribution of Countries

The North American portion of Region 2 contains only four countries: Mexico, the US, Canada, and Greenland. Of these, the US naturally divides into three parts: the contiguous 48 states, Hawaii, and Alaska. Hawaii is naturally isolated from the other service areas and need not be considered here. Alaska, Canada, and Greenland all have very small service arcs because of their high latitudes. Thus, there is little flexibility in choosing satellite positions for services to these countries.

South America contains thirteen countries, none of which has a 20° service arc of less than 47°, and only three of which (Argentina and Chile because of their latitudes, and Brazil because of its size) have 20° service arcs of less than 108°. Central America contains seven countries, and together with the Caribbean islands they form the potential for about 20 service areas or more, all of them comparatively small. None of them has a 20° service arc of less than 112°.

5. SUMMARY AND CONCLUSIONS

The geographic features of latitude, longitude, size, shape, terrain, and climate of a service area all determine the useful service arc for that area, and the locations of service areas relative to one another are the most important factors determining the possibilities of frequency reuse.

Frequency reuse in a large portion of the surface of the earth, such as one of the ITU Regions, is affected significantly by geographic features that allow division into two or more relatively independent subregions. When such division is possible, satellites serving the different subregions may be interpersed allowing spacings as small as one degree, or even collocation in some cases.

As far as frequency reuse in different service areas is concerned, the sidelobe level assumed for the satellite antenna is the most critical factor. The use of shaped beams and sidelobe suppression techniques leads to significant increases in the independence of subregions.

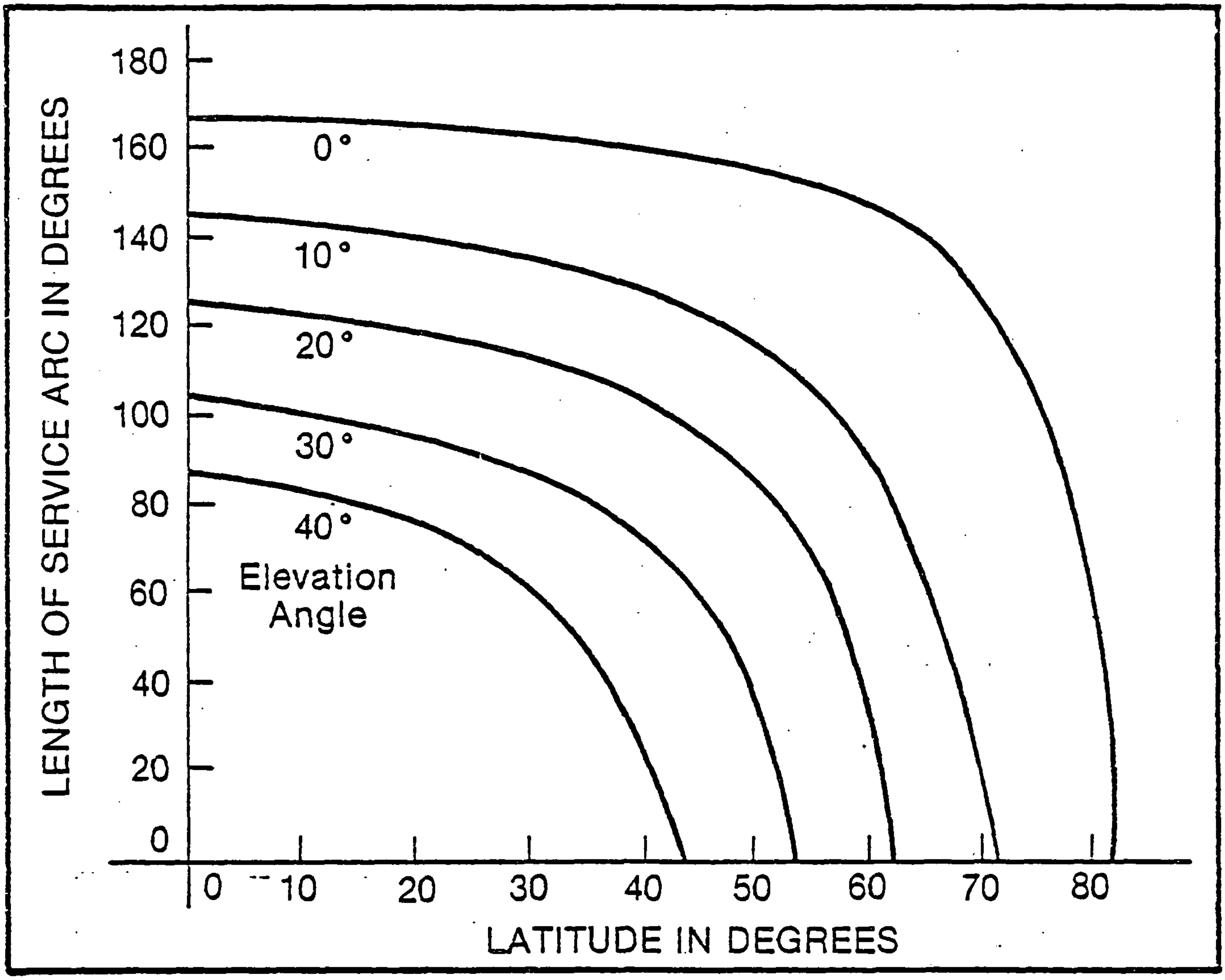

Figure 1. Service Arc of Single Receiver.

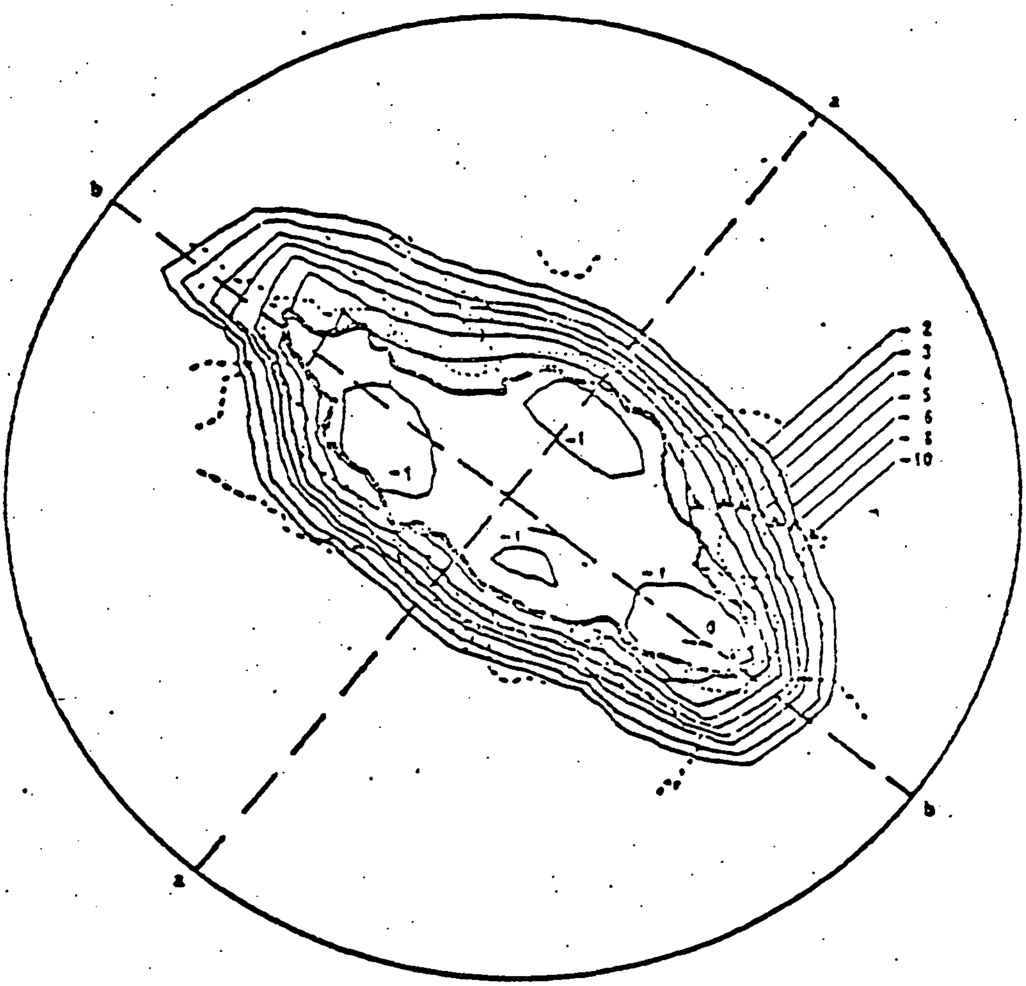

Figure 2. Computed Shaped Beam Pattern for a 21-Horn Parabolic Reflector System.

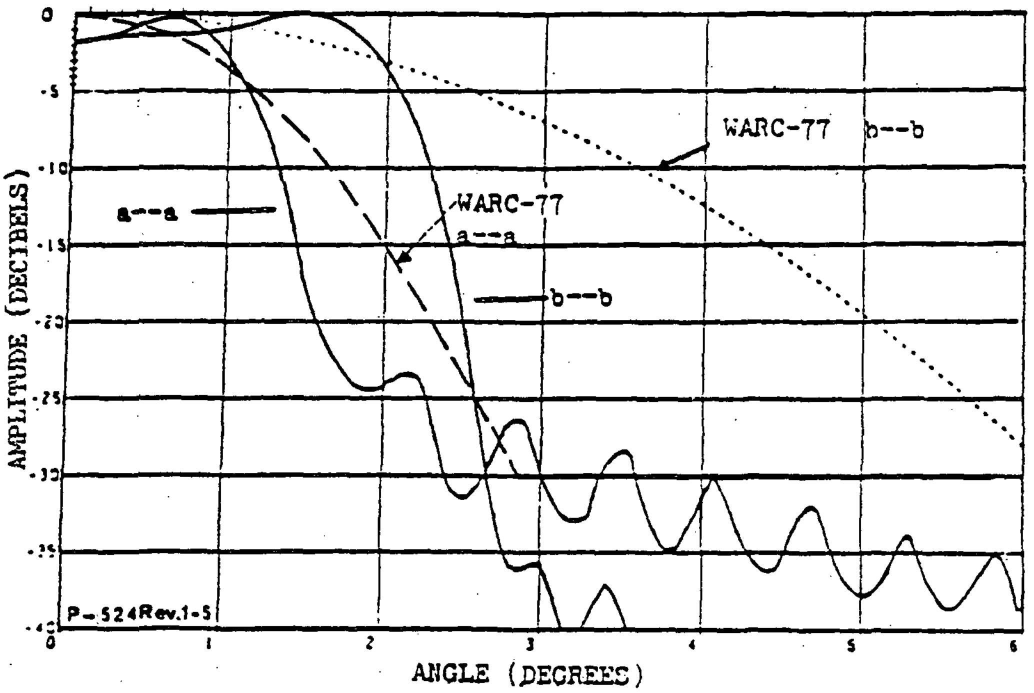

Figure 3. Computed Copoloar Antenna Beam Pattern.

THE UNITED STATES OF AMERICA

DRAFT NEW REPORT

USE OF NONLINEAR PROGRAMMING FOR THE OPTIMIZATION OF SATELLITE ORBITS

INTRODUCTION

This paper describes the application of a nonlinear programming technique to the timization of the orbital positions of a set of non-homogeneous satellites in the fixed-tellite service (FSS). The cochannel protection ratio (either single entry or total) termines the lower limit of the total orbital arc occupied.

NONLINEAR PROGRAMMING (NLP)

2.1 Nonlinear Programming Problem

The nonlinear programming problem can be stated as follows:

Find the set of independent variables, $\bar{x}$, that minimizes the objective function $f(\bar{x})$ subject to the m inequality constraints

$$g_i(\bar{x}) \geq 0, \qquad i = 1, \ldots, m$$

and n equality constraints

$$h_j(\bar{x}) = 0, \qquad j = 1, \ldots n.$$

e or more of f, g, or h is a nonlinear function of the independent variables $\bar{x}$. Any oblem that can be expressed in this form is a nonlinear programming problem and, subject certain limitations, can be solved using nonlinear programming techniques.

2.2 Solution Procedure

Techniques to solve NLP problems use an iterative procedure to minimize the ob-ctive function. Given a solution $\bar{x}$ on the kth iteration, an improved solution $\bar{x}_{k+1}$ is und by the following procedure:

(1) Determine search direction for the independent variables.

(2) Determine step length in this direction.

(3) Accommodate constraints.

(4) Test convergence.

this study a sequential unconstrained minimization technique (SUMT) was used to find the proved solution[1,2]. A similar effort of applying NLP techniques to orbit optimization oblems is described in by Ito et al.[4,5].

With SUMT, the constraints are introduced into the minimization procedure by ding a function of the constraints, the penalty function, to the objective function to rm the modified objective function. The penalty function becomes positive when the constraints are violated, hence the term "penalty." When the constraints are met, the nalty function is zero or becomes zero as the search progresses.

The Davidson-Fletcher-Powell method[3] is used in this study to determine the arch direction to decrease the modified objective function. Once the search direction established, the step length is determined by minimizing the modified objective function this direction. Unidimensional minimization algorithms of Davis-Swann-Campy and well[2] are used. When the modified objective function has converged, the objective function is minimized under the given constraints.

APPLICATION TO FSS ORBIT OPTIMIZATION

3.1 FSS Interference

To apply nonlinear optimization to FSS orbit utilization, one must express the jective function and the interference constraints in terms of the satellite positions. suming cochannel operation and earth-station antenna sidelobe pattern according to CCIR c. 465-1 (Gain = 32 - 25 log θ , where gain is in decibels and θ is in degrees) the terference-to-carrier ratio in the ith system due to interference from the jth system is

$$N_{ji} = K_{ji}\,\theta_{ji}^{\;-2.5}$$

ere K_{ji} is the interference coefficient and

$$\theta_{ji} = |\theta_i - \theta_j| \quad , \quad |\theta_i - \theta_j| \le \theta_i \max$$

$$\theta_{ji} = \theta_{i\,\max} \quad , \quad |\theta_i - \theta_j| > \theta_{i\,\max}$$

and θ_j are the relative longitudes of the ith and jth satellites. No distinction has en made between geocentric angle and topocentric angle. At latitudes of about 40 de-ees, the topocentric angle is approximately 10 percent larger than the geocentric angle.

The interference coefficient is

$$K_{ji} = 1585\ P_j/E_i + F_j/(F_i\ D_i),$$

ere:

P = power into earth station antenna in watts

E = earth station EIRP in watts

F = satellite EIRP in watts

D = downlink receiver gain discrimination factor, defined by

$D = [G(0)/G(\phi)] \cdot \phi^{-2.5}$, where ϕ is the off-axis angle in degrees and G is the antenna gain

The subscripts j and i refer to the interfering and interfered-with systems, respectively.

3.2 Interference Criteria

Three different interference criteria are considered: single entry, scaled ngle entry, and aggregate.

3.2.1 Single Entry Criterion

The single entry criterion requires that the carrier-to-interference tio between any two satellite systems be more than a fixed protection ratio, P. pressing the interference criterion in terms of I/C,

$$N_{ji} \leq 1/P \quad , \quad \begin{array}{l} i = 1, \ldots, n \\ j = 1, \ldots, n \; ; \; j \neq i \end{array}$$

ere n is the number of satellites.

3.2.2 Scaled Single Entry Criterion

The scaled single entry criterion requires that the carrier-to-interferce between any two satellite systems be more than a protection ratio that is a piecese linear function of the spacing between the satellites. In terms of I/C the interferce criterion is,

$$N_{ji} \leq 1/P(\theta_{ji}), \quad \begin{array}{l} j = 1, 2, \ldots, n \\ i = 1, 2, \ldots, n; \; i \neq j \end{array}$$

iere

$$P(\theta_{ji}) = \begin{cases} A & , \quad 0 \leq \theta_{ji} \leq \theta_a \\ A + B \left[\dfrac{\theta_{ji} - \theta_a}{\theta_b - \theta_a} \right] & , \quad \theta_a < \theta_{ji} \leq \theta_b \\ A + B + C \left[\dfrac{\theta_{ji} - \theta_b}{\theta_c - \theta_b} \right] & , \quad \theta_b < \theta_{ji} \leq \theta_c \\ A + B + C & , \quad \theta_{ji} > \theta_c \end{cases}$$

d $\theta_{ji} = | \theta_j - \theta_i |$. Here A, B, C, θ_a, θ_b, and θ_c are parameters that are determined by e particular scaling law used.

3.2.3 Aggregate Criterion

The aggregate interference criterion requires that the carrier-to-interrence ratio in ith satellite system due to interference from all the other salellite stems be more than the total protection ratio for that system, P_i. Expressing this cririon in terms of I/C,

$$\sum_{\substack{j = 1 \\ j \neq i}} N_{ji} \leq 1/P_i \quad , \quad i = 1, \ldots, n$$

3.3 Orbit Optimization

The optimum orbital positions of a set of geostationary FSS satellites is defined to be that order and those positions of the satellites that minimize the total arc occupied by the set within the interference limit constraints.

During the SUMT optimization the total orbital arc of the satellites is progressively compressed until the interference constraints prevent the satellites from further approaching each other. The interference constraints prevent the satellite order from changing during optimization. Therefore, the SUMT solution will converge to the satellite positions that yield the minimum arc for the given satellite order. Other satellite orders may need to be tested to find the smallest minimum arc.

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TRAFFIC COORDINATION IN INTERFERING SATELLITES OPERATING IN THE FIXED-SATELLITE SERVICE

l. INTRODUCTION

The number of communication satellites operating in the same frequency band hat can be placed into the geostationary orbit is limited by mutual radio interference. ;he amount of interference generated by one system and received by another is a com-)lex function of the characteristics of both systems, and for two given systems may de-)end not only on their design parameters but also on the type of traffic carried by them. 'or example, a transponder carrying single-carrier-per-channel traffic is particularly sen-;itive to interference from an FM/TV signal with energy dispersal, while two transpon-iers both carrying single-carrier-per-channel traffic can be made highly compatible by)roper choice of carrier frequencies. By traffic coordination is meant a scheme of match-.ng the traffic assignments in the two systems so as to maximize the compatibility of :ransponders operating at the same frequency.

Traffic coordination as a means of increasing the efficiency of spectrum-orbit ıtilization is mainly applicable to the fixed-satellite service (FSS) and to systems serv-.ng the same geographical area. It is only in the FSS that enough different types of traf-'ic are commonly encountered to make traffic coordination meaningful (FDM/FM voice, 'M/TV, digital data, etc.), and systems serving the same area have greater need for :ooperation because they get no discrimination from the satellite antenna other than pos-;ibly from orthogonal polarization. However, the methods described here can also be ap-)lied to other cooperating systems.

This document describes a possible approach to traffic coordination. The prob-em is formulated in such a way that its solution lends itself to implementation by means)f a digital computer.

!. MEASURE OF COMPATIBILITY

In order to attack the problem of traffic coordination, a quatitative measure must)e attached to the compatibility between two systems. The measure used here is the min-mum spacing required between the satellites of the two systems.

The minimum spacing required between the two satellites is a readily computable unction of the parameters of both systems, technical as well as operational. These pa-ameters include the protection ratios (or equivalently the permissible interference powers) n both systems for the particular types of traffic used, which must be based on a partic-ılar interference budget. This means that the parameters may depend not only on the :haracteristics of the two coordinating systems, but also on the presence of other inter-

-ing systems. To avoid this complication, the single-entry protection ratios can be ed to determine the minimum satellite spacings. Then no systems other than the two ordinating ones need to be considered.

UPLINK-DOWNLINK OPTIONS

In the determination of the minimum required satellite spacings, two cases must considered. If the satellite has no switching capabilities and translates each uplink rrier frequency into a downlink carrier frequency by the same difference frequency, then natching of uplink transponders uniquely determines the matching of the downlink trans-nders. This situation prevails in all domestic systems now in operation.

In the second case, the satellite has a switching capability that allows any re-ived signal to be connected to any output. Then uplink and downlink traffic assign-nts can be made independently. This leads to greater computational complexities in e solution of the traffic coordination problem, but not to greater difficulties in principle.

ASSUMPTIONS

The formulation of the traffic coordination problem will be based on the following sumptions:

a. Both systems use the same transponder configuration, i. e., they have the same number of transponders with the same bandwidths and the same center frequencies.

b. For every pair of signals, one to be assigned to a transponder in one system and the other to a transponder in the other system, there exist four minimum satellite spacing angles, two (one for the uplink and one for the downlink) based on the interference from the first into the second system and two based on the interference from the second into the first system. (A simple way to compute these angles is to base them on the ABCD parameters described in the Report of the Special Preparatory Meeting, Geneva, 1978, Par. 5.3.5.8.4.)

FORMULATION OF THE PROBLEM

Let n be the number of transponders in either system and assume (without loss of nerality) that traffic assignments have already been made to all transponders in one sys-n. Given n signals to be assigned to the n transponders of the other system (which may be different or some of which may be alike), the problem is to make the assignments the second system so as to allow the minimum spacing between the satellites of the two stems. If all signals in both systems are different, there are a total of n! possible as-nment schemes in the case of satellites without switching capabilities. If some of the nals in either or both systems are alike, the number of possible schemes is reduced cordingly. For fully switchable satellites, the maximum number of possible schemes es up to (2 n)!.

Concentrating on the case of satellites without switching capabilities (the exten-n to the other case is obvious), we first select the largest from each set of four angles sociated with the ith signal of the first system and the jth signal of the second system l call it θ_{ij}. This is the minimum separation required between the two satellites in order protect both the transponder of the first system carrying the ith signal and the transpon-of the second system carrying the jth signal assuming that these two are matched, i. e.

assigned to the same carrier frequency. There are a total of n^2 values of θ_{ij}, not necessarily all distinct, which may be arranged as a square matrix called Θ. A particular assignment scheme then consists of the selection of n elements of Θ, one from each row and one from each column. Since the actual required separation of the two satellites is determined by the pair of transponders that requires the largest separation, the problem is to determine the assignment scheme that minimizes the largest element of the selected set.

6. SOLUTION

It is possible, in principle, to examine all n! assignment schemes and select the one (or more) yielding the smallest satellite spacing. But this is a formidable task even for a large digital computer. (Typically, for 12 transponders there may be as many as 12! = 5×10^8 schemes.) It is desirable to use an algorithm that avoids the necessity for an exhaustive search.

If the minimum separation angle were already known, the problem of finding an assignment scheme could be reduced to a simpler one in the following way. Let the minimum separation angle be $\emptyset$. Replace the matrix Θ by a matrix of zeros and ones, called A with elements a_{ij}, so that

$$a_{ij} = 1 \quad \text{if } \theta_{ij} \leqslant \emptyset$$
$$a_{ij} = 0 \quad \text{if } \theta_{ij} > \emptyset.$$

Any selection of n ones from the elements of A, one from each row and one from each column, represents a possible assignment scheme. This however is equivalent to a well known problem, the so-called matching or assignment problem, where n resources (e. g. workers) are to be matched to n demands (e. g. jobs), but not all demands can necessarily be satisfied by each resource. A one at the intersection of a resource row and a demand column means that that particular resource can satisfy that particular demand. A zero means it can not. The matching problem can be solved by a general matching algorithm(1), by the transshipment algorithm(2), or by the Hungarian algorithm(3).

Therefore, a possible approach to the solution of the traffic assignment problem is as follows. Sort the (at most) n^2 distinct values of θ_{ij} into ascending order. Look for the optimum value $\emptyset$ by a binary search. During the search, each value is tested by assuming that it is, in fact, the optimum value and constructing a matrix A of zeros and ones based on this assumption. One of the available assignment-problem algorithms is then used to find a possible assignment scheme. If none can be found, the test value was too small and the search is continued with the higher binary search value of θ_{ij}. If one (or more) schemes are found, the test value is either optimum or too large, and the search is continued with the lower binary search value of θ_{ij}. The search ends when a value is found for which one or more assignments are possible, with no smaller value of θ_{ij} allowing any assignments.

The number of steps in this procedure is of the order of $n^3 \log_2 n$, which for n = 12 is about 10^4. Even though the computational complexity of each step in this procedure may be as much as an order of magnitude greater than that in the steps of an exhaustive search, this still represents a vast reduction from n!. In this estimate, the factor n^3 arises from the steps needed to solve the matching problem, and $\log_2 n$ is the number of values of $\emptyset$ used in the binary search.

As an example, Figure 1 shows a typical matrix Θ for two satellites with twelve ansponders each. The element in the second row and third column, for example, is 4.9 nd means that, if the second transponder of the the first system and the third transponder f the second system were assigned the same carrier frequency, then the satellites would ave to be spaced at least 4.9° apart in order to keep the interference below the required alue in both systems.

Using a trial value of 4.0° for $\emptyset$, the matrix A of Figure 2 was constructed by re- lacing all elements of Θ that are greater than 4.0 by zeros and the remaining ones by ones. he problem now is to find at least one way of selecting twelve ones from this matrix so 1at there is one from each row and one from each column. In this particular case, it is lear that there is no solution since the 8th row consists of all zeros, and therefore no one an be selected from this row. Hence, the trial value of 4.0° is too small. When the trial alue of 4.2° is used, the resulting matrix A is shown in Figure 3. Now solutions are pos- ible, and one of the several solutions is given by the twelve underlined ones. All the pos- ible solutions in this case are, in fact, optimal, and any one of them leads to an optimal affic assignment scheme.

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$$
\Theta = \begin{pmatrix}
3.4 & 4.8 & 4.8 & 5.2 & 3.1 & 5.5 & 4.2 & 3.9 & 6.2 & 3.5 & 4.0 & 5.1 \\
2.5 & 4.1 & 4.9 & 3.9 & 6.1 & 5.5 & 3.7 & 3.9 & 5.1 & 6.2 & 5.2 & 4.9 \\
3.6 & 3.6 & 3.8 & 6.0 & 2.8 & 4.5 & 4.8 & 6.2 & 3.6 & 3.9 & 4.1 & 3.8 \\
2.9 & 2.3 & 5.7 & 5.6 & 6.9 & 7.7 & 3.0 & 3.5 & 5.4 & 4.0 & 3.3 & 5.1 \\
5.2 & 6.1 & 4.6 & 4.8 & 4.0 & 3.9 & 6.2 & 3.5 & 3.5 & 2.7 & 4.6 & 4.9 \\
5.2 & 6.1 & 4.6 & 3.9 & 5.6 & 5.5 & 3.0 & 4.2 & 6.3 & 6.0 & 5.3 & 4.6 \\
3.7 & 3.5 & 2.9 & 4.6 & 6.1 & 4.7 & 4.6 & 4.2 & 3.8 & 6.0 & 3.0 & 4.4 \\
4.7 & 4.3 & 5.3 & 5.0 & 4.8 & 6.3 & 5.9 & 4.2 & 4.4 & 4.4 & 5.3 & 6.0 \\
3.9 & 3.5 & 4.6 & 5.7 & 4.8 & 6.3 & 4.0 & 3.8 & 5.5 & 4.7 & 4.7 & 3.4 \\
5.0 & 5.8 & 6.0 & 4.7 & 4.6 & 5.3 & 6.0 & 6.0 & 3.8 & 4.4 & 4.7 & 3.8 \\
6.3 & 6.6 & 5.1 & 4.0 & 5.7 & 5.8 & 2.7 & 6.2 & 4.8 & 4.0 & 5.2 & 6.3 \\
4.6 & 4.8 & 4.0 & 3.9 & 3.2 & 4.8 & 5.0 & 4.6 & 3.0 & 3.9 & 4.9 & 6.1
\end{pmatrix}
$$

Figure 1. Example of Matrix Θ (12x12).

$$
A = \begin{pmatrix}
1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \\
1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 1 \\
1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0
\end{pmatrix}
$$

Figure 2. Matrix A for Ø = 4.0°. (No solution.)

$$
A = \begin{pmatrix}
\underline{1} & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\
1 & 1 & 0 & \underline{1} & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\
1 & 1 & \underline{1} & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\
1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & \underline{1} & 0 \\
0 & 0 & 0 & 0 & 1 & \underline{1} & 0 & 1 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & \underline{1} & 1 & 0 & 0 & 0 & 0 \\
1 & \underline{1} & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \underline{1} & 0 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & \underline{1} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \underline{1} & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & \underline{1} & 0 & 0 \\
0 & 0 & 1 & 1 & \underline{1} & 0 & 0 & 0 & 1 & 1 & 0 & 0
\end{pmatrix}
$$

Figure 3. Matrix A for Ø = 4.2°. (Solution underlined.)

APPENDIX D

PAPERS PRESENTED AT TECHNICAL CONFERENCES

THE EFFECTS OF GEOGRAPHY ON SPECTRUM-ORBIT UTILIZATION

Peter H. Sawitz

ORI, Inc., Silver Spring, Md. 20910

ABSTRACT

Geography has been a neglected factor in many general analyses of communication satellite systems. However, geographical features, such as latitude, size, shape, terrain, and climate of a service area, can have important effects, particularly on the service arc from which useful service can be provided to an area and on the possibilities of frequency reuse, which is the single most important factor affecting the efficiency of spectrum-orbit utilization. This paper discusses the effects of geography on service arcs and on the various techniques used to achieve frequency reuse. Particular emphasis is given to fixed and broadcasting satellite systems.

1. INTRODUCTION

The unique advantages of the geostationary orbit for communication and other satellites are well known. More than forty satellites already have been launched into this orbit, most of them to operate in the fixed-satellite service (point-to-point) (FSS), and many more are planned. The Plan adopted in 1977 for broadcasting satellites calls for 26 satellites to serve Europe, Africa, Asia, and Australia. Even now, there is considerable crowding at certain locations for satellites operating in the FSS at 4 and 6 GHz, and it is becoming increasingly difficult to find suitable orbit positions for new systems operating at those frequencies. As a result, much effort is currently being spent on increasing the efficiency of spectrum-orbit utilization by improved technology or operating procedures.

One proposed solution to this problem is to make detailed usage plans, assigning to each country orbital positions and frequencies to be used at each position. It is alleged that this assures equitable distribution of the available scarce resource. However, such a plan may result in inefficient spectrum-orbit utilization because it must of necessity be based on the technology at the time of adoption of the plan, and because some potential users may not use their assignments for many years, having neither immediate requirements nor the necessary economic resources.

A detailed plan, made for the entire world or for a part thereof, naturally takes into consideration all the geographic features of the areas served. However, a more flexible approach can take these features into consideration also, though in a more general way. This becomes important, for example, in making estimates of the capacity of the spectrum orbit resource and in making comparisons between rigid plans and more flexible approaches.

In the past, the effects of geographic features have often been neglected in general analyses, and as a result some misleading conclusions have been drawn. This paper discusses these features in detail and assesses their effects and importance. It mainly deals with communication satellites operating in the FSS or broadcasting-satellite service (BSS). Most of the results, however, are also applicable to other services, such as meteorology and navigation.

2. FREQUENCY REUSE

The key to efficient spectrum-orbit utilization is frequency reuse. If each frequency (or band of frequencies) were used only once, the capacity of the spectrum orbit resource would simply be the total number of communication channels that can fit into the available bandwidth. The number of satellites in orbit would be irrelevant, as would be their positions and the distribution of service areas.

Frequency reuse is possible primarily through three techniques: orthogonal polarization, earth-station antenna discrimination, and satellite antenna discrimination. Geographic features have some effects on all three techniques; but the one most affected is the satellite antenna discrimination. All three will be discussed below.

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3. SERVICE ARCS

The service arc of an area is defined as that portion of the geostationary orbit from which useful service can be provided to all points in that area. the emphasis here is on "useful". The service arc is not identical with the visible arc. Visibility, i. e., the existence of an unobstructed line-of-sight path, is a necessary but not a sufficient condition for useful service. Other conditions that must be satisfied are elevation angles that exceed minimum values and, for some services, eclipse protection.

Elevation angles are important because many propagation impairments, such as natural and man-made noise and rain attenuation, increase with decreasing elevation angle. The minimum elevation angle required is a strong function of the rain statistics, particularly for frequencies above 10 GGz. Thus, the geographic feature of climate has a significant effect on the service arc of an area. Service areas with high average rain rates require higher elevation angles, and therefore have smaller service arcs.

As an example of the rapid increase of attenuation with decreasing elevation angle, Figure 1 shows the attenuation as a function of elevation angle at 12 GHz[1]. Figure 2 shows the rain zones of the world as defined by the International Telecommunications Union (ITU) in the Radio Regulations. It is interesting to note that most of the areas with high rain rates lie at low latitudes.

Another geographical feature that affects the minimum elevation angle required is the terrain. If deep valleys surrounded by high mountains are to be served from satellites, visibility may be greatly restricted at low elevation angles. Thus, for some services, areas with mountaneous terrain may have smaller service arcs than flat ones with otherwise similar characteristics.

4. EFFECT OF LATITUDE

For a single receiver located at a given point, and for an assumed minimum elevation angle, the length of the service arc is a function of latitude only. Figure 3 shows the length of the service arc for such a point as a function of latitude for elevation angles from 0° to 40°. For an area that is narrow in latitude, so that all its points are aproximately at the same latitude, this length will be decreased by the difference in longitude between the easternmost and westernmost points. Figure 3 clearly shows how the service arc decreases with latitude, slowly at first, and then with increasing rapidity. It also shows the severe restrictions on elevation angles at the higher latitudes.

5. EFFECTS OF SIZE AND SHAPE

The service arc of an extended area of irregular shape is determined by the latitudes and longitudes of the two points on the boundary of the area at which the elevation angle first falls below the given minimum value as the satellite moves east or west, as the case may be. These points frequently are not obvious by inspection and must be determined by trial and error or by graphical means.

In general, the larger the service area, the smaller its service arc. For example, the service arc of Brazil, a very large country, is about 83° at 20° elevation angle, while that of the much smaller Paraguay, which is at about the same latitude, is about 108°.

As far as shape is concerned, a long narrow area has a smaller service arc than a roughly circular one of the same size. However, for long areas that are not roughly parallel to a line of latitude, the most extreme latitude is usually more important than the length.

6. ORTHOGONAL POLARIZATION

The discrimination obtainable between two crosspolarized beams depends on two geographical features: the climate (which determines the rain statistics) and the relative locations of the areas served by the beams. Depolarization caused by rain is an important effect both with linear and with circular polarization. The variation of the received polarization angle with latitude and longitude, which may or may not be significant depending on the antenna characteristics, will be present only with linear polarization. Both these effects are discussed in detail in an ITU report[2].

7. SATELLITE ANTENNA DISCRIMINATION

Of the three techniques that make frequency reuse possible, the satellite antenna discrimination is the one most dependent on geographical factors, namely on the separation of the service areas.

The discrimination obtainable from the satellite antenna depends on its gain pattern. In the absence of more specific information, the Consulative Committee for International Radio (CCIR), the technical arm of the ITU, recommends two reference patterns, one for the FSS and one for the BSS. The two patterns are shown in Figure 4. The FSS pattern was adopted in 1974 and has not been changed since then. The BSS pattern was adopted in 1977 and reflects the advances in technology of the intervening years. Because of that, the BSS pattern has been used in the computations made here.

According to the BSS antenna reference pattern, the maximum discrimination possible is the

on-axis gain, which can be as high as 49 dB for a very small beam of about 0.6° width, or as low a 32 dB for a large beam of about 3.5° width. This value is reached when the receiver is about 18 beamwidths away from beam center. A value of 35 dB is frequently used for the necessary protection ratio between two systems. Thus it is clear that the entire discrimination required can be obtained from the satellite antenna discrimination only in exceptional cases. The earth subtends about 17.3° at the satellite. Hence, for 1° beams, there are no areas that can be served at the same frequency from the same or colocated satellites without excessive interference. Only with very small beams and for widely separated service areas will such service be possible.

However, the antenna pattern used has a plateau that gives 30 dB of discrimination at points that are between 1.6 and 3.2 beamwidths away from beam center. Thus, very little additional discrimination is required to make frequency reuse possible. This can be obtained from the earth-station antenna by using two satellites that need very little separation. To show this, the required separation angles between pairs of satellites of four different systems have been computed for coincident service areas and for service areas separated by 1.6 beamwidths. The relevant parameters for the four systems are listed in Table 1 and the required separation angles (for a 35 dB protection ratio) are listed in Table 2. The effect of area separation is dramatic.

Table 1
Typical Systems Parameters

	System	Antenna Diameter m	Satellite EIRP dBw	Band-width MHz
1	BSS, Indiv. Recep.	1.0	64	18
2	BSS, Commu. Rec.	1.8	56	23
3	FSS, High Capac.	7.0	52	160
4	FSS, Low Capacity	4.5	46	16

Table 2
Satellite Spacing Required (Degrees)

Interfering Systems	Separation of Service Areas	
	Coincident	1.6 Beamwidths
1 and 1	18.8	1.2
1 and 2	18.2	1.3
1 and 3	12.9	1.0
1 and 4	18.2	1.3
2 and 2	9.8	0.8
2 and 3	6.3	0.6
2 and 4	8.8	0.7
3 and 3	2.6	0.4
3 and 4	3.7	0.4
4 and 4	3.6	0.4
Frequency: 12 GHz		

8. EARTH-STATION ANTENNA DISCRIMINATION

The effect of geography on the earth-station antenna discrimination is a minor one. It comes about because of the variation of the ratio of topocentric to geocentric angle with latitude and relative longitude. This ratio varies from a maximum of 1.18 at locations near the subsatellite point and for geocentric angles less than about 15° to a minimum of 0.99 at locations near the edges of the field of view or for geocentric angles near 90°. While these variations are small, they may be significant because, in some regions of the antenna patterns, the discrimination varies rapidly with off-axis angle.

9. FEATURES OF REGION 2

Region 2, as defined by the ITU, comprises essentially the Western Hemisphere. The two outstanding geographical features of this region in the context of this paper are its isolation from the other two Regions and its natural subdivision into three subregions. This subdivision, which is easily revealed by a look at the map, is also recognized by the usual nomenclature: South America, Central America, and North America. Greenland, which is part of Region 2, is not formally part of North America, but geographically it appears as an appendix thereof.

10. FEATURES OF REGIONS 1 AND 3

While Regions 1 and 3 have the same isolation from Region 2 as Region 2 has from them, there is practically no isolation between the two. Region 1 consists essentially of Europe, Africa, all of the USSR, and Mongolia. Region 3 comprises the rest of Asia and Australia and New Zealand. There are no clear geographical demarcations between them. From the point of view of satellite coverage, the two must be considered as a single region.

Furthermore, Regions 1 and 3 do not show any well defined subregions, with the exception of New Zealand. Neither the Mediterranean Sea, which separates Europe and Africa, nor the various bodies of water that separate Australia, Indonesia, and the main land of Asia are wide enough to give an appreciable amount of satellite discrimination unless very small service areas or, equivalently, shaped beams are used.

11. CONSEQUENCES

The consequences of all this are somewhat different for the FSS and the BSS. For international coverage, the FSS requires either very large area coverage, possibly using a global beam, or two somewhat smaller beams when oceans are to be spanned. For domestic systems, country coverage is usually desired, which requires large beams for large countries. The BSS will normally have beams that cover no more than one or two time zones, so

that very large beams are not likely to be required.

In all Regions, coloation of satellites serving different areas and operating at the same frequencies will be possible only in rare instances. But widely separated areas can be served from closely spaced satellites, separated by 1.5° or less. Thus a high density of satellites is possible leading to efficient spectrum-orbit utilization.

There is little interaction between Region 2 and Regions 1 and 3. But Regions 1 and 3 are strongly linked to each other and must be considered as a single region.

In Region 2, the operation of satellites in both services in North and South America are relatively independent. Central America has strong interactions with the other two subregions, but comparative independence still exists because the likely service areas in Central America all have large service arcs.

In Regions 1 and 3, subregions are more difficult to define, but there also widely separated areas are relatively independent. However, the absence of well-defined subregions will decrease the possibilities of frequency reuse. The choice of small service areas and the increased use of shaped beams will counteract these restrictions.

The small service arcs of the countries located at high latitudes (Alaska, Canada, Greenland, Scandinavia, and the USSR) greatly decrease their flexibility in providing satellite services. At many locations in these countries the desirable elevation angles cannot be achieved at all.

12. REFERENCES

1. ITU, Broadcasting Satellite Conference, Final Acts, Geneva 1977.
2. "Factors to be Considered in the Choice of Polarization for Planning the Broadcasting-Satellite Service", CCIR Report 814, Geneva 1978.

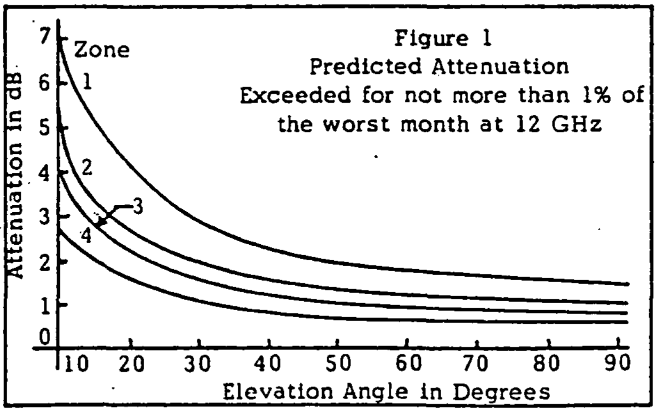


Figure 1
Predicted Attenuation
Exceeded for not more than 1% of the worst month at 12 GHz

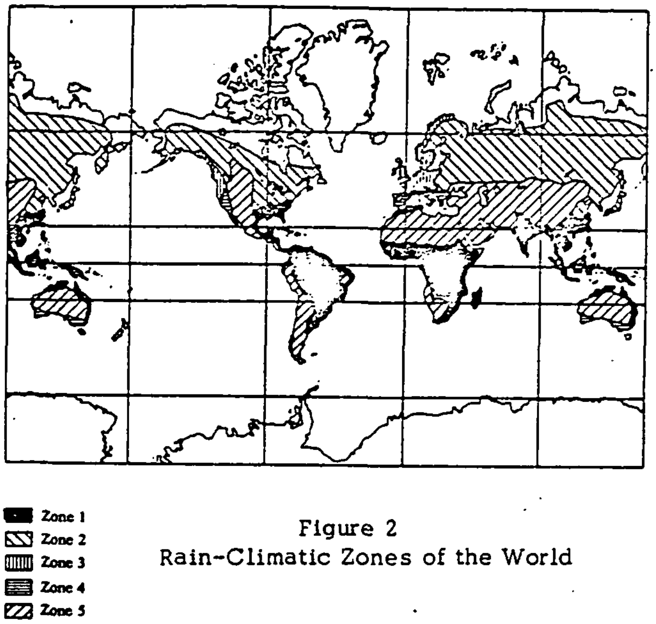
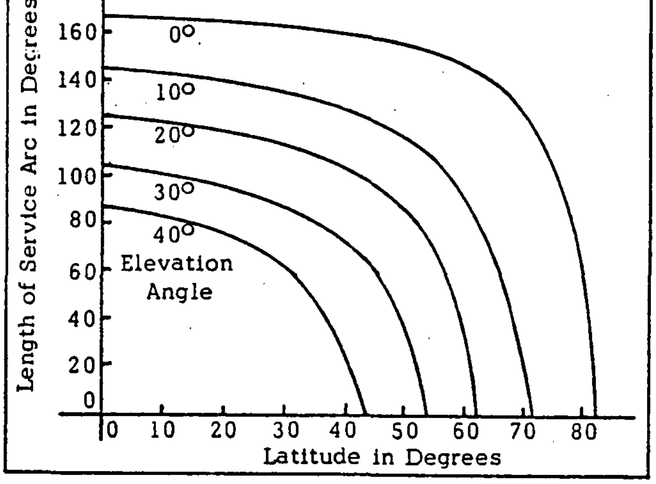


Figure 2
Rain-Climatic Zones of the World

Figure 3. Service Arc of Single Receiver.



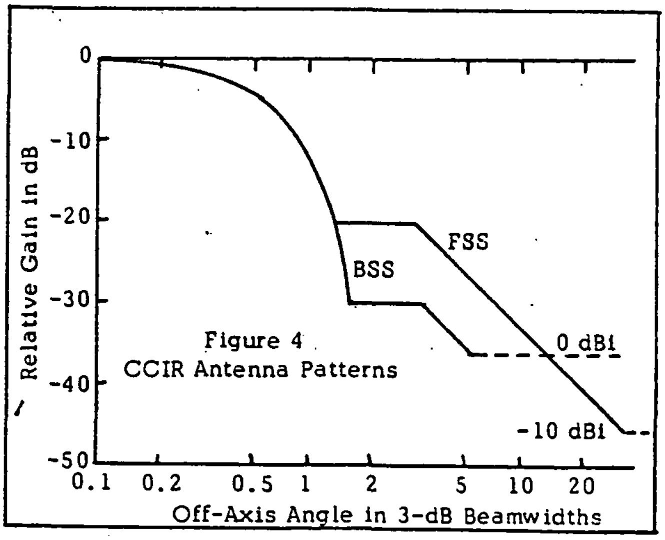


Figure 4
CCIR Antenna Patterns

THE EFFECTS OF GEOGRAPHY ON DOMESTIC FIXED AND BROADCASTING SATELLITE SYSTEMS IN ITU REGION 2*

Peter H. Sawitz
Principal Scientist
ORI, Inc.
Silver Spring, Maryland

ABSTRACT

Geographical features, such as latitude, size, shape, terrain, and climate of a service area, can have significant effects on the extent of the orbital arc from which useful service can be provided and on the possibilities of frequency reuse, which is the single most important factor determining the efficiency of spectrum-orbit utilization. This paper discusses the effects of geography on service arcs and on the various techniques used to achieve frequency reuse and applies the results to the domestic fixed and broadcasting satellite systems of ITU Region 2.

1. Introduction

The International Telecommunications Union (ITU) divides the surface of the earth into three Regions. Region 1 essentially contains Europe, Africa, all of the USSR, and Mongolia. Region 3 comprises the rest of Asia and Australasia. Region 2 essentially contains the Western Hemisphere and Greenland. Region 2 is of special interest for at least three reasons. There are at this time more satellites in orbit providing domestic services in the fixed-satellite service (FSS) in Region 2 than in the other two Regions combined. Until very recently, only in Region 2 did the FSS have an allocation in the 11.7 to 12.2 GHz frequency band, sharing this band with the broadcasting-satellite service (BSS). And last not least, Region 2 includes the USA.

Both the FSS and the BSS are using, or plan to use, the geostationary orbit for reasons that are well known. More than sixty satellites already have been launched into this orbit, most of them to operate in the FSS (point-to-point) both for international and for domestic services. The 1977 World Administrative Radio Conference for Broadcasting Satellites (77 WARC-BS) adopted a plan for the BSS which calls for 26 broadcasting satellites to serve ITU Regions 1 and 3. Even now, there is considerable crowding at certain locations for satellites in the FSS operating in the 4 and 6 GHz frequency bands, and it is becoming increasingly difficult to find suitable orbit positions for new systems operating in these bands.

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One proposed solution to this problem is to make detailed usage plans, assigning to each country or group of countries orbital positions and frequencies to be used at each position. It is alleged that this assures equitable distribution of the available scarce resource. However, such a plan may result in inefficient spectrum-orbit utilization because, being based of necessity on the technology prevailing at the time of its adoption, it cannot make use of subsequent advances, and because some potential users may not use their assignments for many years, having neither immediate requirements nor the necessary economic resources.

A detailed plan, made for the entire world or for a part thereof, naturally takes into consideration all the geographic features of the area served. However, a more flexible approach can take these features into consideration also, though in a more general way. This becomes important, for example, in making estimates of the capacity of the spectrum-orbit resource, and in making comparisons between rigid plans and other approaches.

In the past, the effects of geographic features have often been neglected in general analyses, and as a result some misleading conclusions were drawn. For example, a study by Reinhart[1] on spectrum-orbit sharing between the FSS and the BSS, which expounds all the important principles of sharing between these two services and became the basis for United States policy for many years, stops short of considering the effects of the specific geographic features of the areas to which the principles were applied. This paper discusses these features in detail and assesses their effects and importance.

2. Background

The 77 WARC-BS adopted a plan for the BSS in Regions 1 and 3. It also called for a Regional Administrative Radio Conference in 1983 for the purpose of planning the BSS in Region 2. The recently concluded General World Administrative Radio Conference of 1979 adopted a resolution to hold a special conference in the near future on planning the space services in all frequency bands allocated to them. Thus, the broad problems of how best to plan the BSS and FSS so as to meet the legitimate requirements of all nations are constantly being reexamined and will be the topics of two future international conferences. The information presented in this paper is meant to be a contribution to the solution of

these planning problems.

3. Spectrum-Orbit Utilization

Both the frequency spectrum and the geostationary orbit are limited natural resources. The limitations of the frequency spectrum arise from mutual interference. It is less obvious, but true nevertheless, that the limitations of the geostationary orbit arise from the same source. Thousands of satellites could be placed in that orbit without danger of physical interference. But when they operate in the same frequency band, considerations of radio interference require satellite separations that vary from a degree or less to as much as twenty degrees or more, depending on the system characteristics. Therefore, the two resources are usually grouped together. The general topic of providing the maximum amount of useful services from the geostationary orbit within a given frequency band is referred to as spectrum-orbit utilization.

While the capacity of the spectrum-orbit resource, whatever is used as its measure, is not infinite, one cannot assign a definite number to it unless both the technical characteristics of all systems involved and their operational modes are completely specified. In fact, the capacity has steadily increased in recent years as technology has advanced, and there are ample reasons to believe that this trend will continue. It is for this reason that it is so important to factor all available information, including the geographical features of the intended service areas, into the planning process. Then a flexible approach can be used that allows the identified requirements to be met at each epoch without foreclosing the utilization of technological advances in the future to meet new and expanding requirements of all nations.

4. Frequency Reuse

The key to efficient spectrum-orbit utilization is frequency reuse. If each frequency, or band of frequencies, were used only once, the capacity of the spectrum-orbit resource would simply be the total number of communication channels that can fit into the available bandwidth. The number of satellites would be irrelevant, as would be their positions and the distribution of service areas. There would be no interference, except perhaps between adjacent channels.

Frequency reuse is possible primarily through three techniques: orthogonal polarization, earth-station antenna discrimination, and satellite antenna discrimination. Geographic features have some effects on all three; but the one affected most is the satellite antenna discrimination. All three will be discussed below.

5. Service Arcs

The service arc of an area is defined as that portion of the geostationary arc from which useful service can be provided to all points in that area. The emphasis here is on "useful". The service arc is not identical with the visible arc. Visibility, i. e. the existence of an unobstructed line-of-sight path, is a necessary but not a sufficient condition for useful service. Other conditions that must be satisfied are elevation angles that exceed certain minimum values and, for some services, eclipse protection.

Elevation angles are important because many service impairments, such as natural and man-made noise and attenuation due to rain, increase with decreasing elevation angles. The minimum elevation angle required for satisfactory service is a strong function of the rain statistics of an area, particularly at frequencies above about 10 GHz. Thus, the geographical feature of climate has a significant effect on the service arc of an area. Service areas with high average rain rates require higher elevation angles and therefore have smaller service arcs. Systems in the FSS usually require minimum elevation angles of ten to fifteen degrees, except in areas with very high rain rates. Systems in the BSS may require minimum elevation angles of twenty to as high as forty degrees. Of course, such high elevation angles are not always possible at high latitudes. Then more elaborate (and more expensive) receiving systems will be required, or a lower quality of service must be accepted.

As an example of the rapid increase of attenuation with decreasing elevation angle, Figure 1 shows the attenuation due to rain as a function of elevation angle at 12 GHz[2]. Figure 2 shows the rain zones of the world as defined by the ITU in the Radio Regulations. It is interesting to note that most of the areas with high rain rates lie at low latitudes.

Most satellites in geostationary orbit are powered by solar cells. Twice a year, for periods of about 44 days centered on each of the equinoxes, they pass through the shadow of the earth every night. This eclipse lasts only a few minutes at the beginning and end of the eclipse period, but increases to a maximum of 72 minutes on the equinoxes themselves. During these times, the satellite is without solar power and therefore inoperative unless it carries enough batteries. For high-powered satellites, such as are usually assumed for direct-to-the-home broadcasting, this could be an excessive burden. The eclipse is centered on midnight local time at the subsatellite point. By "eclipse protection" is meant a satellite position sufficiently west of the service area so that the eclipse will not occur during the time considered essential for providing services. For direct-to-the-home broadcasting, eclipse protection is usually interpreted to mean that the eclipse should occur no earlier than one a. m. in the time zone of the service area. While the eclipse is not a geographical feature, it does impose serious restrictions on the service area if protection is required, decreasing it to less than half of what it would be otherwise. It thus combines

with the geographical features in affecting spectrum-orbit utilization.

Figures 3 and 4 show the service arcs of some likely service areas in North, South, and Central America for elevation angles of 10 degrees and, whenever possible, also for 20 and 40 degrees without regard to eclipse protection.

6. *Effect of Latitude*

For a single receiver located at a given point and for an assumed minimum elevation angle, the length of the service arc is a function of latitude only. Figure 5 shows the length of service arc for such a point as a function of latitude for elevation angles of zero, ten, twenty, thirty, and forty degrees. For an area that is narrow in latitude, so that all of its points are approximately at the same latitude, this length will be decreased by the difference in longitude between its easternmost and westernmost points. The curves of Figure 5 clearly show how the service arc decreases with latitude, slowly at first, and then with increasing rapidity at higher latitudes. They also show the severe restrictions on elevation angles at the higher latitudes.

7. Effects of Size and Shape

The service arc of an extended area of irregular shape is determined by the latitudes and longitudes of the two points on the boundary of the area at which the elevation angle first falls below the given minimum value as the satellite moves east or west, as the case may be. These points frequently are not obvious by inspection and must be determined by trial and error or by graphical means. In general, the larger the service area, the smaller its service arc other things remaining equal. For example, the service arc of Brazil, a very large country, is about 83 degrees at 20 degrees elevation angle, while that of the much smaller Paraguay, which is at about the same latitude, is about 108 degrees.

As far as shape is concerned, a long narrow area has a smaller service arc than a roughly circular one of the same size. However, for long areas that are not roughly parallel to a line of latitude, the most extreme latitude is usually more important than its length.

8. Orthogonal Polarization

The discrimination obtainable between two crosspolarized beams depends on two geographical features: the climate (which determines the rain statistics) and the relative locations of the areas served by the beams. Depolarization caused by rain is an important effect with both linear and circular polarization. The variation of the received polarization angle with latitude and longitude, which may or may not significant depending on the antenna characteristics, is present only with linear polarization. Both these effects are discussed in detail in a report by the Consultative Committee on International Radio (CCIR)[3].

9. Earth-Station Antenna Discrimination

The effect of geography on the earth-station antenna discrimination is a minor one. It comes about because of the variation of the ratio of topocentric to geocentric angle with latitude and relative longitude. This ratio varies from a maximum of 1.18 at locations near the subsatellite point and for geocentric angles less than about 15 degrees to a minimum of 0.99 at locations near the edges of the field of view of the satellite or for geocentric angles near 90 degrees. At locations in the United States and for geocentric angles that are not too big, the value of 1.1 is a good approximation. While the variations are small, they may be significant because, in some regions of the antenna patterns, the discrimination varies rapidly with off-axis angle.

10. Satellite Antenna Discrimination

Of the three techniques that make frequency reuse possible, the satellite antenna discrimination is the one most dependent on geographical factors, namely the separation of service areas.

The discrimination obtainable from the satellite antenna depends on its gain pattern. In the absence of specific information about the actual antennas, the CCIR, the technical arm of the ITU, recommends two reference patterns, one for the FSS and one for the BSS. These two patterns are shown in Figure 6. It is seen that the sidelobe envelope of the BSS pattern lies ten decibels below that of the FSS pattern, except at very large off-axis angles. The reason for this is not some fundamental difference between BSS and FSS satellites, but rather the different times of adoption. The FSS pattern was adopted in 1974 and has not been changed since then. The BSS pattern was adopted in 1977 and reflects the advances in technology in the intervening years. Because of that, the BSS pattern has been used in all computations made here. The results will change when shaped beams and sidelobe reduction techniques now under intensive investigation are incorporated into future systems.

According to the BSS reference pattern, the maximum discrimination obtainable is the on-axis gain. This can be as high as 49 dB for a very small beam about 0.6 degrees wide between 3-dB points, or as low as 32 dB for a large beam of about 3.5-degree width. A value of 35 dB is frequently used for the required single-entry protection ratio, corresponding to a total protection ratio, considering the combined interference from all other satellite systems, of about 31 dB. The value of 35 dB is reached, if at all, at a point about five beamwidths away from beam center. Hence, frequency reuse from the same satellite, or from colocated satellites, is possible provided that the satellite beams are no wider than about three degrees and that the separation between areas using the same frequencies is at least five beamwidths. Such service are-

as cannot easily be found within the United States, or even within the combined areas of the United States and Canada, under reasonable assumptions. But such areas do exist in the combined areas of North, Central, and South America. (These results apply strictly only to homogeneous systems, but they are valid approximately in non-homogeneous systems also as long as the non-homogeneities are not too great.)

However, substantial values of discrimination from the satellite antenna are available at points with much smaller separations. The antenna pattern used has a plateau that gives a discrimination of 30 dB at points that are between 1.6 and 3.2 beamwidths away from beam center. Thus, very little additional discrimination is required to make frequency reuse possible. This additional discrimination can be obtained from the earth-station antenna when the two areas are served by two different satellites. The separation required between the two satellites depends on the additional discrimination required.

To show this in more detail, the separation angles required between pairs of satellites of four different systems have been computed for coincident service areas and for service areas separated by 1.6 beamwidths. To compute these angles, it was assumed that the relevant parameters of the four systems are those listed in Table 1; that the frequency is 12 GHz; that the BSS earth-station receiving antennas have the characteristics adopted by the 77 WARC-BS for Region 2; that the FSS earth-station receiving antennas follow the CCIR reference sidelobe pattern (gain = $32 - 25 \log \theta$, where the gain is in decibels and the off-axis angle θ is in degrees); that this last reference pattern is valid for angles smaller than one degree, contrary to the CCIR recommendations; that the required protection ratio is 35 dB for the BSS and 32 dB for the FSS; that the BSS reference pattern of Figure 6 is valid for the FSS as well as the BSS; and that the ratio of topocentric to geocentric angle is 1.1 in all cases. Furthermore, 0.2 degrees were added to all separation angles to account for a station-keeping tolerance of 0.1 degrees for satellites, and possible differences in center frequencies and bandwidths used by the various systems were ignored, i. e., it was assumed that all interfering power from one (and only one) system was received by the other. For a service-area separation of 1.6 beamwidths, the discrimination was taken to be 27 dB, the difference between the 30-dB discrimination from the satellite antenna and the 3-dB gain reduction of a receiver at the edge of its service area. The resulting separation angles are listed in Table 2. It is seen that the effect of area separation is dramatic.

For adjacent service areas, the beam coverages usually overlap. In that case, the satellite antenna discrimination may be negative at some points. For then it is possible for a receiver that is located at or near the edge of its own service area to be on a higher gain contour of the interfering beam than of its own. Then the values of the required satellite separation angles may be substantially larger than those listed in Table 2 for coincident service areas.

Table 1. Typical System Parameters.

	System	Antenna diameter m	Satellite EIRP dBw
1	BSS, indiv. recep.	1.0	64
2	BSS, commu. recep.	1.8	56
3	FSS, high capacity	7.0	52
4	FSS, low capacity	4.5	46

Table 2. Satellite Spacing Required (Degrees).

Interfering Systems	Separation of Service Areas: Coincident	1.6 Beamwidths
1 and 1	19.0	1.8
1 and 2	18.3	1.7
1 and 3	6.4	0.7
1 and 4	14.0	1.3
2 and 2	8.9	0.9
2 and 3	6.2	0.7
2 and 4	6.8	0.8
3 and 3	2.0	0.4
3 and 4	4.8	0.6
4 and 4	2.8	0.4

11. Features of Region 2

The two outstanding geographical features of ITU Region 2, from the viewpoint of spectrum-orbit utilization, are its isolation from the other two Regions and its natural subdivision into three subregions.

The three ITU Regions are shown on a world map in Figure 7. It may be seen that the boundaries of Region 2, both on the east and on the west, are entirely over water. And, with the exception of Iceland and eastern Siberia, there are no significant inhabited land masses outside the boundaries and close to them. Furthermore, both the eastern and the western boundaries run in a generally north-south direction. These features greatly reduce the interaction between services in Region 2 and services in Regions 1 and 3. With the satellite-antenna gain patterns used here, a separation of 1.6 beamwidths (where a discrimination of 30 dB is reached) seems to be a reasonable criterion for "strong" interactions. With that definition, only three areas in Region 2 can have strong interactions with areas in Regions 1 or 3: Alaska and eastern Siberia, Greenland and Iceland, and eastern Brazil and western Africa.

Also, there is comparatively little overlap of the service arcs of Region 2 and those of Regions 1 and 3. On the east, the arc from about zero to forty degrees west longitude is useful for many countries both in South America and in Africa and Europe. In fact, this potential conflict was explicitly recognized by the 77 WARC-BS and resulted in some

special provisions of its Final Acts. On the west, the overlap between the service arcs of Alaska and those of eastern Siberia, New Zealand, and some parts of Australasia do not appear to be significant. Thus, as may be seen from Figures 3 and 4, in most of the arc useful to Region 2, satellites can be placed with almost complete disregard of the interactions with the satellites serving Regions 1 and 3. No similar features exist to isolate Regions 1 and 3 from each other. In fact, from the point of view of spectrum-orbit utilization, they must be considered as a single region.

Figure 8 shows a possible coverage pattern for Region 2 in which the medium-size and the large countries are covered by single beams and the smaller countries are grouped together (without regard to political alliances) and covered by regional beams. The obvious subdivision into three subregions is evident. It is the same as that recognized by common nomenclature: South America, Central America, and North America. Greenland, which is part of Region 2, is not formally part of North America, but geographically it is an appendage thereof. The relative independence of North and South America is based on the geographical fact that no service area in either one of these two subregions is less than 1.5 beamwidths away from any beam center in the other. On the other hand, the service areas of Central America have "strong" interactions with either North or South America or both. But these service areas are comparatively small and lie at low latitudes, so that their service arcs include portions that are useful to the countries of North and South America only marginally or not at all.

Figure 9 shows another coverage pattern for Region 2 in which no two countries are covered by the same beam and the larger countries are covered by many beams. The conclusions arrived at above will hold a fortiori for the smaller beams of this case.

Another feature of the division into subregions is the geographical fact that most of South America lies entirely to the east of most of North and Central America. While the east-west separation between South America and the rest of Region 2 is not as pronounced as the north-south separation, it does lead to the existence of a portion of the orbital arc (east of about 40 degrees west longitude, the very same portion that is also useful to some countries in Region 1) that is useful to South America, but not to North America. However, considerations of eclipse protection will make the eastern portions of their service arcs less attractive to the countries of South America. All this is made less important by the fact that all countries of South America, because of their size or latitude, have comparatively large service arcs.

12. Consequences

One of the consequences of these features is that Region 2 on the one hand and Regions 1 and 3 on the other can use different approaches to planning if they so desire, as in fact they have done at the 77 WARC-BS for the BSS at 12 GHz. Another consequence is that planning services both in the FSS and the BSS for North and South America can proceed relatively independently. But planning for Central America must be coordinated closely with both North and South America, and vice versa.

As was pointed out before, the same satellite (or colocated satellites) can provide services at the same frequencies to areas that are separated by about five beamwidths or more. Figure 7 shows that no two service areas in Region 2 are separated by angles as big as that with the large beams used in that example. With the smaller beams assumed in Figure 9, there are two South American service areas (southern Chile and southern Argentina) that are sepseparated sufficiently from all of the US and Canada to allow colocated satellites. Some Canadian service areas and Alaska could be paired with many more South American ones for colocation of satellites. But it is unlikely that there will be satellites providing services exclusively to these northernmost regions without also having beams covering more southern areas. On the other hand, practically all of the South American service areas are separated sufficiently from the US and Canada to allow satellite spacings of 1.5 degrees or less. Considering the satellite spacings of 6 degrees adopted by the 77 WARC-BS for the broadcasting satellites of Regions 1 and 3, and recalling the spacings listed in Table 2, which give very small values only for the unrealistic cases of exclusive use of very large earth-station antennas, satellite spacings of less than four degrees are not likely to be useful in any subregion. Thus, even though colocation of satellites will be possible only in exceptional cases, the satellites serving North and South America can generally be interspersed without compromising the freedom of planning for either subregion.

It must be emphasized that the specific results given are based on the antenna patterns adopted by the 77 WARC-BS. The use of shaped beams and sidelobe reduction techniques would increase the relative independence of subregions and extend the applicability of the results to many portions of Central America.

13. References

1. "Orbit-Spectrum Sharing between the Fixed-Satellite and Broadcasting-Satellite Services with Applications to 12 GHz Domestic Systems" by Edward E. Reinhart. R-1463-NASA, May 1974, The Rand Corporation, Santa Monica, California 90406.

2. ITU, Broadcasting Satellite Conference, Final Acts, Geneva 1977.

3. "Factors to be Considered in the Choice of Polarization for Planning the Broadcasting-Satellite Service", CCIR Report 814, Geneva 1978.

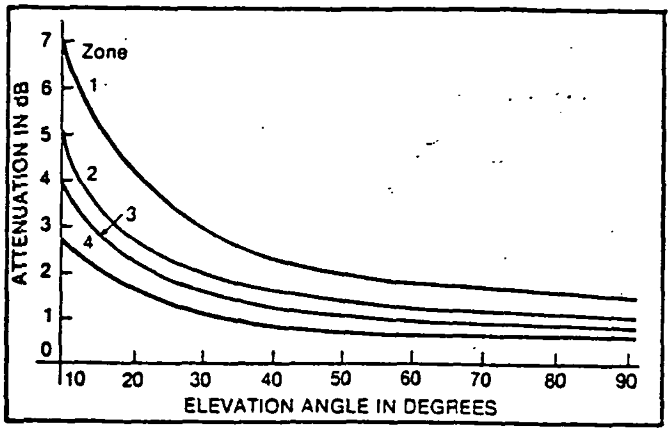

Figure 1. Predicted Attenuation Exceeded for not More than 1% of the Worst Month at 12 GHz.

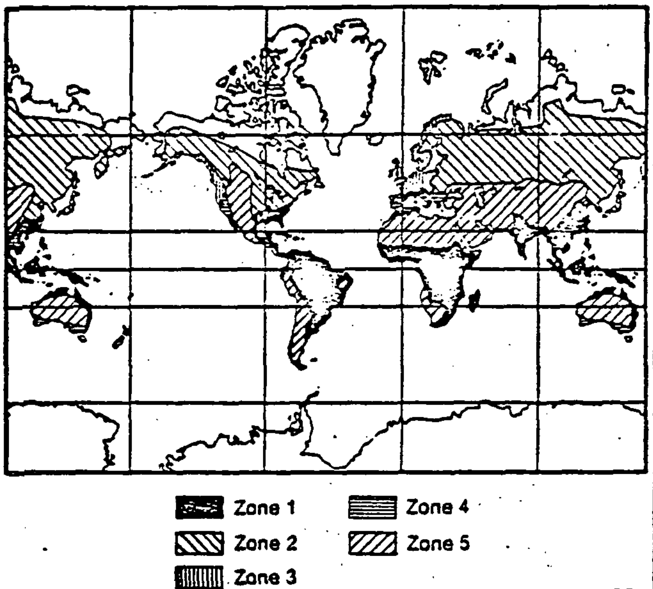

Figure 2. Rain-Climatic Zones of the World.

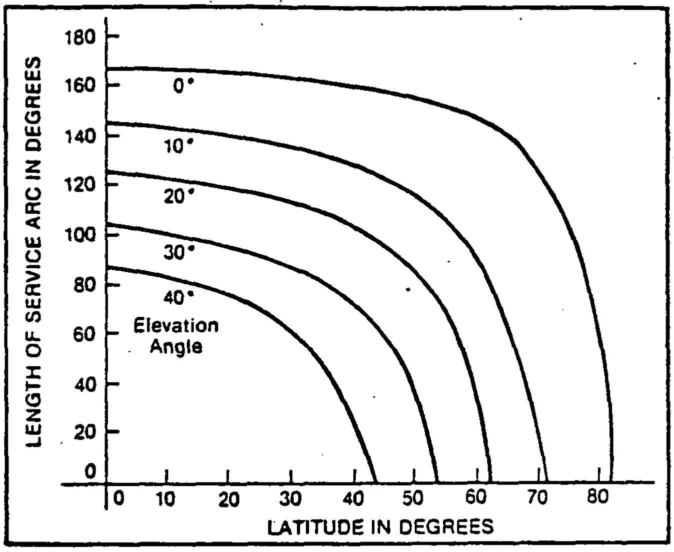

Figure 5. Service Arc of Single Receiver.

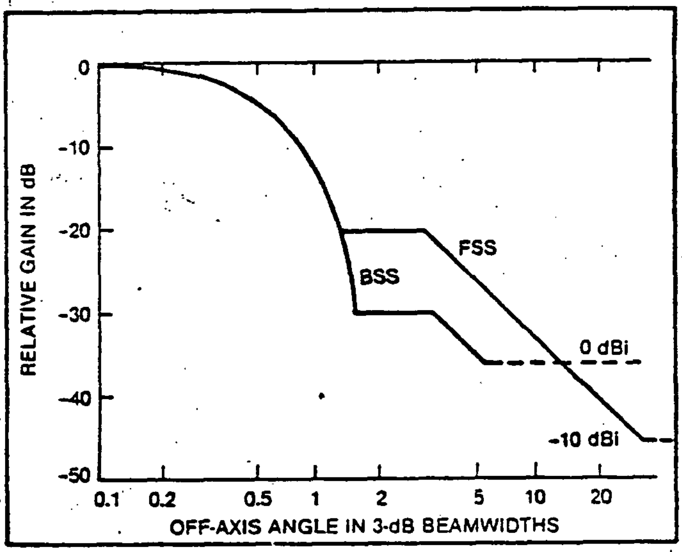

Figure 6. CCIR Antenna Patterns.

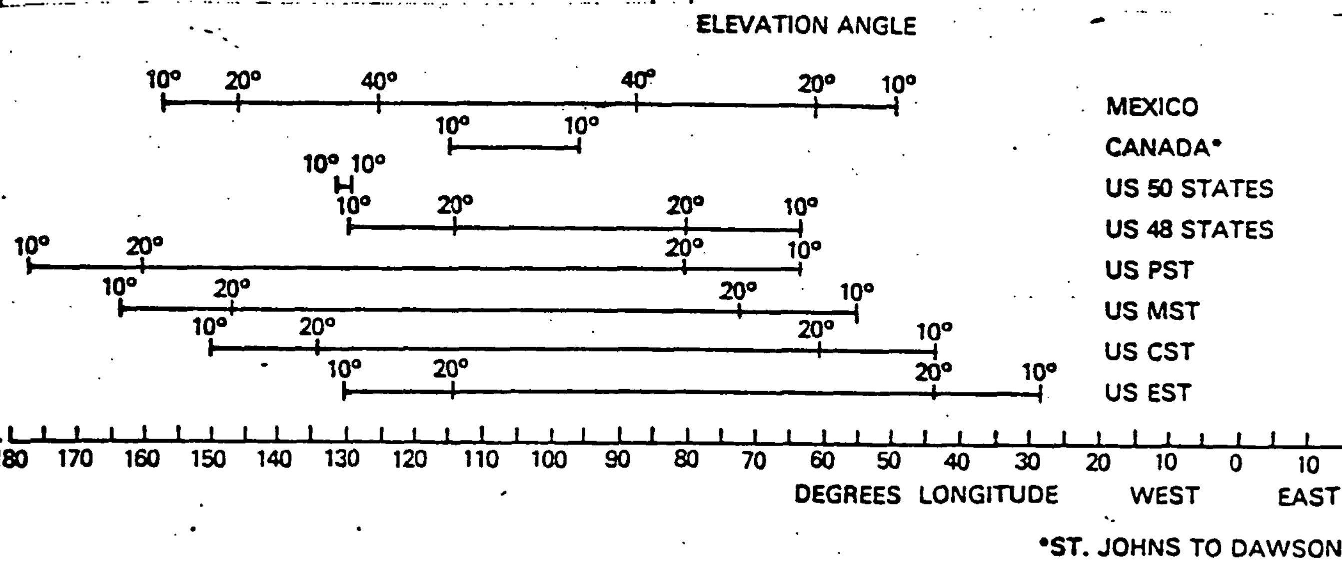

Figure 3. Service Arcs for North America.

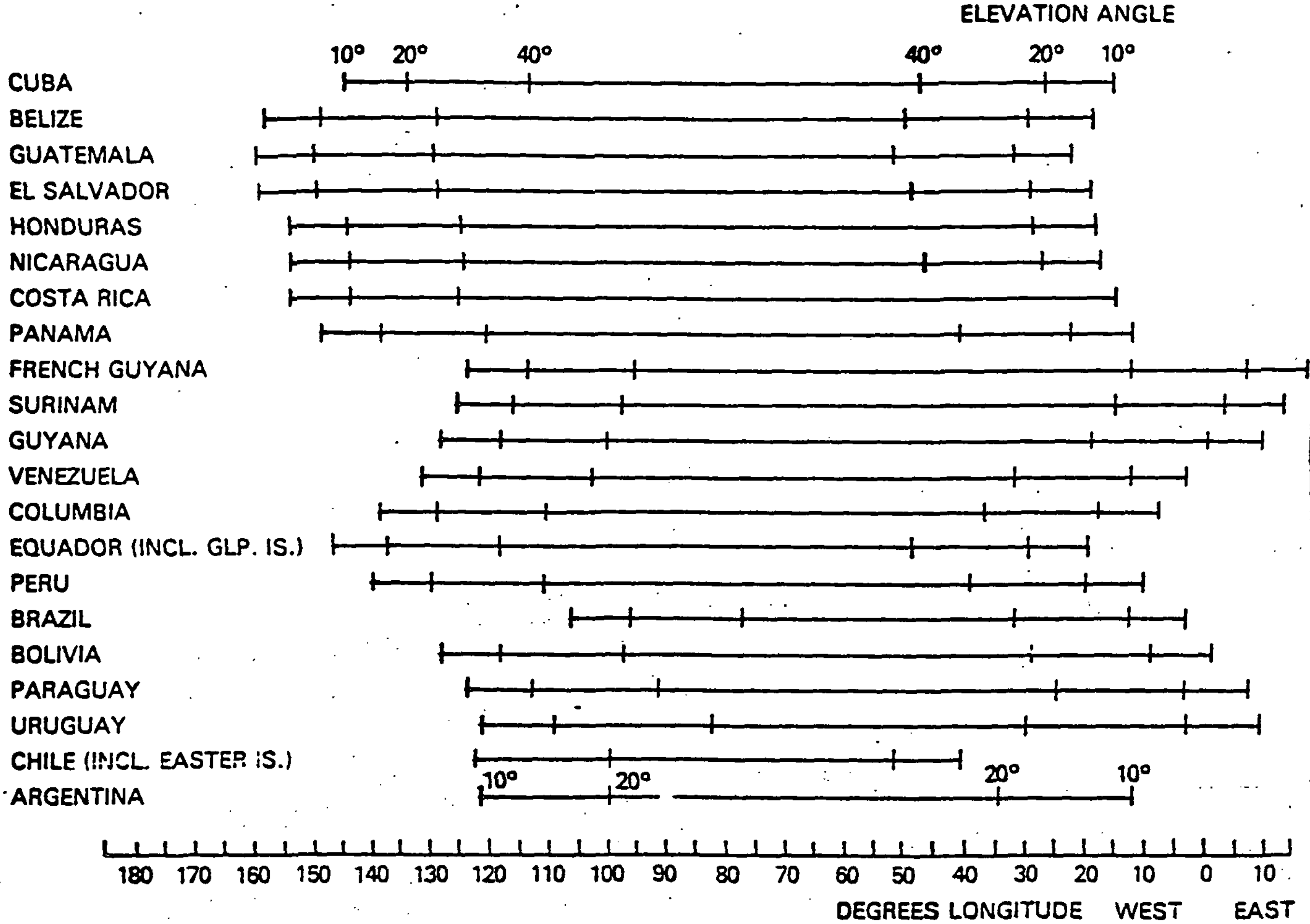

Figure 4. Service Arcs for South and Central America.

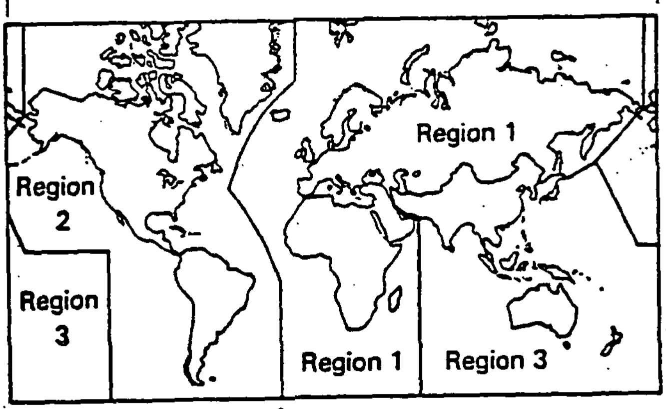

Figure 7. ITU Regions of the World.

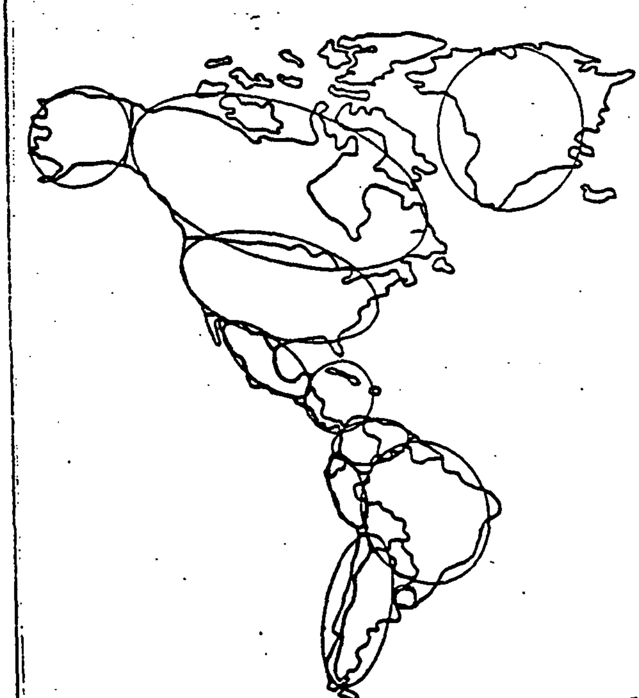

Figure 8. Large-Beam Coverage of Region 2.

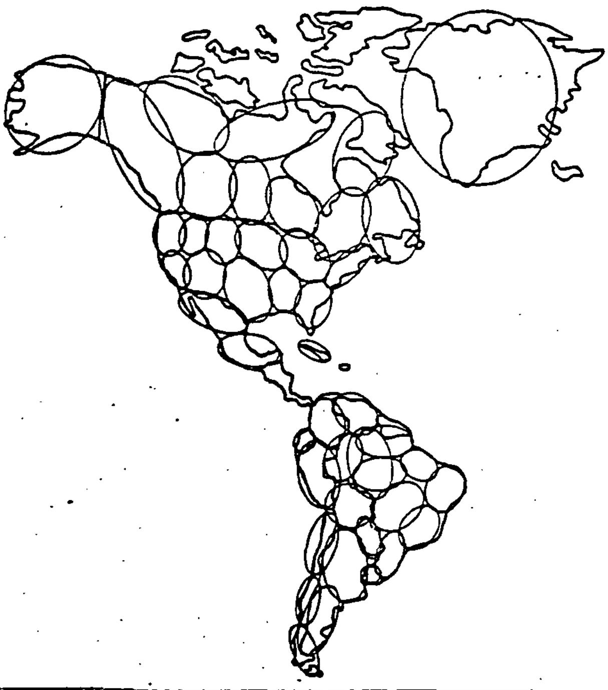

Figure 9. Small-BeamCoverage of Region 2.

APPENDIX E

RESPONSES TO SPECIFIC REQUESTS

MEMORANDUM FOR DR. AKIMA

From: Peter Sawitz
Date: October 15, 1979
Subject: Channel-Orbit Plan for BSS in US and Canada

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1. ASSUMPTIONS

The BSS is for individual reception only. Earth-station receiving antennas have 1 m diameter (1.8° 3-dB beamwidth).

Earth-station receiving antenna patterns and satellite transmitting antenna patterns are as specified in Final Acts of 1977 WARC-BS. Satellite antenna beams are elliptical or circular.

There are 10 service areas in the US and 10 service areas in Canada, approximately as shown in Figures 1 and 2.

Cochannel and adjacent channel protection ratios (total) are 31 dB and 14 dB, respectively.

Channels are 23 MHz wide and spaced 20 MHz apart. Adjacent channels have opposite polarization.

There are 12 channels in 250 MHz total bandwidth. Channels are labeled consecutively from 1 to 12. There are four channel groups as follows:

f_1: 1, 3, 5

f_2: 7, 9, 11

f'_1: 2, 4, 6

f'_2: 8, 10, 12

Channels 6 and 7 do not overlap.

Eclipse protection (1 a.m.) is desirable, but not absolutely necessary.

All channels for a given service area come from the same satellite and with the same polarization.

All satellites have the same on-axis EIRP. (This was taken to be 62 dBw, but the actual value is irrelevant for interference studies.)

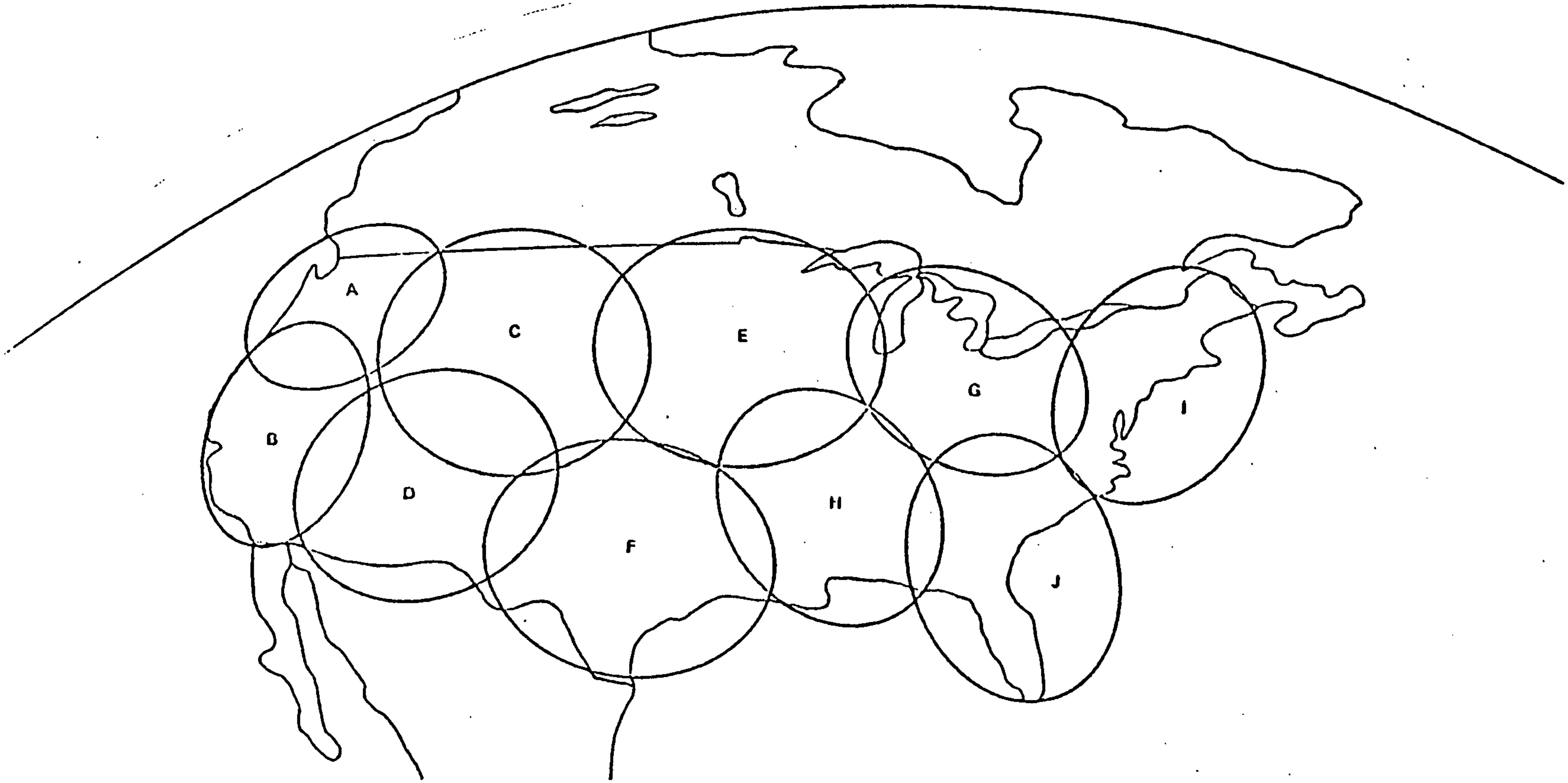


Figure 1. US Service Areas.

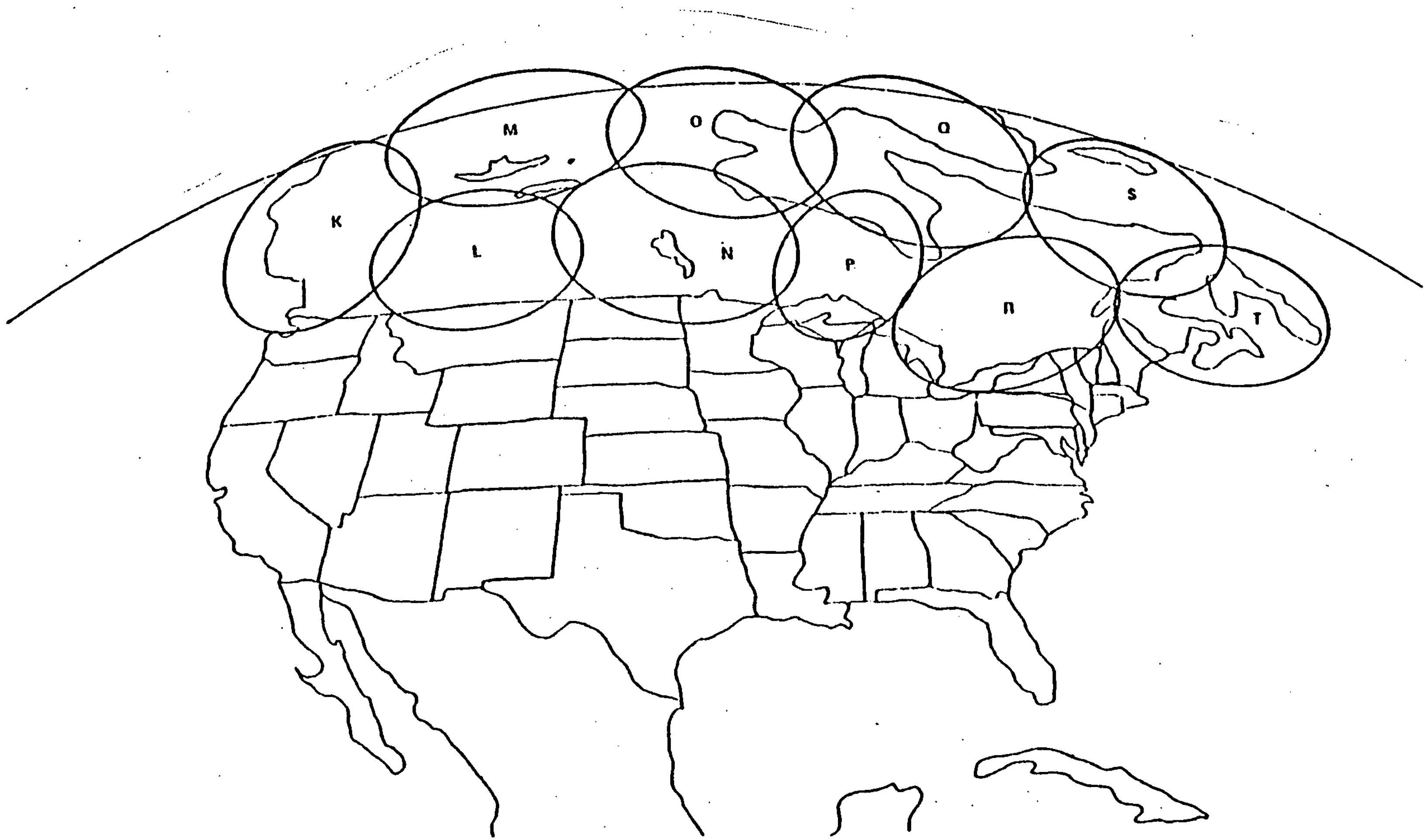


Figure 2. Canadian Service Areas.

2. THE PLAN

The plan tested is shown in Table 1. Satellites are spaced 10° apart. A total of 6 satellites are used. Two of these, one each for the US and Canada, use all four groups of frequencies, the others use only three groups. (The unused groups could be used by Central America and the Caribbean Islands.) An attempt was made to use a total of only 5 satellites, having each use all four groups of frequencies and sharing one between the US and Canada, but no such scheme was found feasible.

Table 2 shows the available service arc for each service area assuming a minimum elevation angle of 20° and full (1 a.m.) eclipse protection. It is seen that this protection is not achieved for every service area. It could be achieved only at the expense of using more satellites (and fewer channel groups from each). Neither the elevation angle nor the eclipse requirements can be met in the northernmost parts of Canada.

3. RESULTS AND DISCUSSION

Table 3 lists the margins at the worst test points for each service area as obtained from the computer simulation program. It is seen that there are four negative margins, two in the US and two in Canada. The two in the US are both greater than -1 dB (-0.2 and -0.6 dB) and may be considered insignificant. They could probably be removed by making minor adjustments to the beams involved.

The smallest margin of -6.7 dB occurs in Area K in Canada and is caused by interference from beam F in the US, the beam serving Texas and Oklahoma. It is believed that this beam as chosen extends too far north, and that it could be reduced in size without impairing the quality of service in its own service area. This would reduce the negative margin in Canada and might eliminate it altogether. It is intended to make further computer runs with this beam adjusted.

The other negative margin in Canada (in area R, -2.2 dB) arises from interference between two Canadian beams, R and N. It is believed that these beams can be adjusted to eliminate this negative margin.

The results obtained to date show that a satisfactory plan can be designed based on the stated assumptions.

With 10 service areas each in the US and Canada, only one quarter of the total number of channels can be used in any one service area. Hence, 3 channels per service area (C/SA) is the maximum possible in a total of 250 MHz. This result is independent of whether the US and Canada use the same 250 MHz or different, nonoverlapping bands.

With 10° satellite separation, both South and Central America (including the Caribbean Islands) can be served from interspersed satellites. If these satellites are located at 95°, 105°, etc., the result would be a plan with 5° spacing between satellites (as compared to the 6° used in the Plan for Regions 1 and 3). However, the required spacing for all satellites serving South America is considerably less than five degrees, and therefore the plan assumed for the US and Canada

Table 1. BSS Plan for US and Canada.

	SERVICE AREA	CHANNEL GROUP	SAT. POSIT. DEG. W
US	A	f_1	
	B	f_2	140
	C	f_1'	
	D	f_2'	
	E	f_1	
	F	f_2	120
	H	f_2'	
	G	f_1'	
	I	f_1	110
	J	f_2	
CANADA	K	f_2'	
	L	f_2	130
	M	f_1	
	N	f_2'	
	O	f_1'	
	P	f_2	100
	Q	f_1	
	R	f_1'	
	S	f_1'	90
	T	f_2	

Table 2. Service Arc Limits for 20° Elevation Angle and 1 a.m. Eclipse Protection

SERVICE AREA	EASTERN LIMIT DEG. W	WESTERN LIMIT DEG. W.	REMARKS
A	135	160	
B	135	160	
C	120	146	
D	120	146	
E	105	134	
F	105	134	
G	90	114	
H	105	134	
I	90	114	
J	90	114	
K	135	139	20° SATISFIED IN BC ONLY
L	120	122	
M	120	122	20° NOT SATISFIED
N	105	118	
O	105	118	20° NOT SATISFIED
P	90	92	
Q	90	92	20° NOT SATISFIED
R	90	92	
S	90	92	20° NOT SATISFIED
T	75	84.2	

Table 3. Margins at Worst Test Points.

	SERVICE AREA	COPOL. dB	CROSSP. dB	TOTAL dB
US	A	4.6	15.3	4.3
	B	0.01	12.9	-0.2
	C	17.3	25.6	16.7
	D	6.1	21.5	6.0
	E	9.0	25.5	8.9
	F	15.0	27.5	14.7
	G	4.3	19.8	4.2
	H	2.6	14.9	2.4
	I	-0.5	18.1	-0.6
	J	0.8	16.8	0.7
CANADA	K	-6.5	7.2	-6.7
	L	10.6	25.2	10.5
	M	9.1	37.9	9.0
	N	1.6	19.5	1.5
	O	3.6	19.6	3.5
	P	4.3	18.4	4.2
	Q	6.2	24.7	6.2
	R	-2.2	22.8	-2.2
	S	3.4	25.5	3.4
	T	13.1	16.8	11.6

places only minor restrictions on the planning for the rest of Region 2. On the other hand, the plan assumed would preclude almost entirely the use of the same frequency band for other broadcasting satellite uses, e. g. for community reception.

If only 4 service areas are assumed for the US, no frequency reuse within the US would be possible because of the size of the service areas. Therefore, the number of C/SA would still be three.

With 6 service areas in the US (possibly one each for the PST and MST zones, and two each for the CST and EST zones), it is believed that frequency reuse may be possible. Then, if the US and Canada use different frequency bands, the number of C/SA in the US would double to 6. However, the US band would then be denied to Mexico and Central America also. A plan using 6 service areas and 6 C/SA has not been tested as yet.

ORI, Inc.
1400 Spring Street
Silver Spring, Maryland 20910

Telephone: (301) 588-6180

March 14, 1980

Dr. Hiroshi Akima
NTIA/ITS
Section 2
325 Broadway
Boulder, Colorado 80303

Dear Hiroshi:

After careful review of your work on modifications of Annex I of CCIR Report 814 (Doc. USSG BS/849), I have come to the conclusion that the best way to correct the error in that Annex is to replace the words "horizontal plane" with "horizontal line" and to add a definition of horizontal line. We are all grateful to you for having pointed out this error to us. I am enclosing a copy of the correction that I am submitting to Study Group 10/11B for approval.

I hope we can all agree that, with this correction, Annex I is correct and that the equation given is, in fact, the correct equation for computing the angle Θp as now defined. I am also enclosing my derivation of this equation.

I realize that there are two additional points that you are trying to make in your work. The first is that, while the conclusions of Annex I (namely that a horizontally polarized wave from the satellite cannot be relied on to be orthogonal to a vertically polarized terrestrial system at all locations) are valid, they should be based on a consideration of the angle between the polarization angle of the incident wave and the local horizontal plane rather than the local horizontal line. The second is that, in making the point, one should take into consideration the location of the aim point of the satellite antenna, rather than assume that "the longitude of the boresight of the beam is the same as the satellite longitude." I must disagree with you on both these points.

As to the first, it is common practice to resolve the polarization vector of a wave arriving at a point on the ground from an arbitrary direction into its horizontal and vertical components. The horizontal component lies, by definition, in the local horizontal plane and therefore along the local horizontal line since all components must be perpendicular to the propagation vector. The vertical component is perpendicular to the horizontal one, but does not lie, in general, along the local vertical. Only the vertical component evokes a response from a vertically polarized antenna, and it is the angle between the polarization vector and the local horizontal line that determines the magnitude of this component. Of course, the vertical component may not evoke a full response either, but this effect is taken care of by the gain pattern of the antenna.

As to the apparent discontinuity of the received angle of polarization in Figure 1 of Annex I at the origin, this is easily explained by the fact that at this point the wave polarization is horizontal regardless of the direction of the polarization vector. At a point slightly north of the origin, the local horizontal line is in the equatorial plane. Thus the received angle of polarization (as defined in the corrected Annex I) is zero. At a point slightly east or west of the origin, the local horizontal line is perpendicular to the equatorial plane and the received angle of polarization is ninety degrees. At all points near the origin the antenna response is very low because the direction of the incoming wave is practically perpendicular to the boresight of the terrestrial receiving antenna. Whether this response is obtained from the copolarized antenna pattern (as it would be for an observer on the equator) or from the crosspolarized pattern (as it would be for an observer on the zero meridian) is not really important and becomes an arbitrary choice at the origin itself.

As far as the aim point of the satellite antenna is concerned, I do not think that it matters for the purpose of the report. The figure implies an incident wave from a certain direction (on the equator at zero relative longitude) and with a certain polarization (parallel to the equatorial plane). It does not matter how this incoming wave was produced. In particular, it does not matter where the antenna that produced it was pointed. Of course, the assumption that the polarization vector is parallel to the equatorial plane is an arbitrary one. Instead, one could have assumed that the polarization vector is parallel to the local horizontal plane at some given point on the surface of the earth. But then one could simply define a new spherical coordinate system with its origin at the center of the earth such that its polar axis passes through the given point. The polarization vector would again be parallel to the new "equatorial plane" and Figure 1 would simply be rotated. Thus no assumptions need be made about the aim point of the antenna producing the incoming wave.

I am looking forward to seeing you at our next 10/11B meeting. Perhaps we can discuss this further then.

Sincerely,

Peter H. Sawitz
Communications Systems Division

PHS/ch

cc: J.E. Miller
Ed Reinhart

Documents
CCIR Study Groups
Period: 1978-1982

Doc. USSG-BC/
12 March 1980
Original: English

Received:

Subject: Study Programs 20C-2/10 and 5G-2/11

The United States of America

MODIFICATION OF REPORT 814

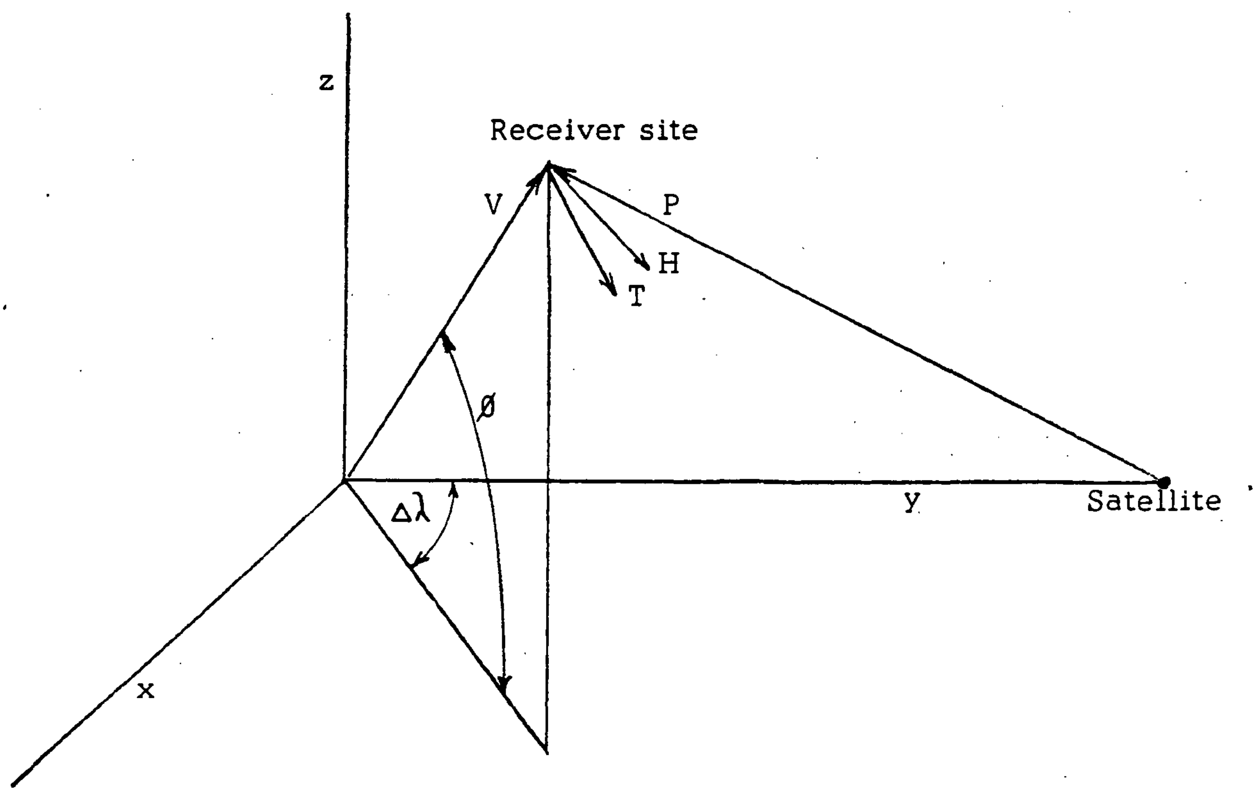
The following modification should be made in Annex 1 of Report 814, pg. 303 of volume XI of the Recommendations and Reports of the CCIR, 1978, in the definitions of the terms of the equation for θ_p:

θ_p: polarization angle of the incident wave relative to the local horizontal ~~plane~~ line, i. e., the line in the local horizontal plane that is perpendicular to the line from the satellite to the ground receiving terminal,

Derivation of the equation for the angle θ_p given in CCIR Report 814, Annex 1 (pg. 303 in Volume XI of 1978 Green Books).

Notation (see Figure)

V	=	unit vector along the local vertical at receiver site
P	=	vector from satellite to receiver site
ϕ	=	latitude of receiver site
$\Delta\lambda$	=	longitude of receiver site relative to subsatellite point
T	=	unit vector along the polarization of the incoming wave, assumed to be parallel to the equatorial plane
H	=	local horizontal line = unit vector in the local horizontal plane at the receiver site perpendicular to P



x-y plane is the equatorial plane
Satellite is assumed to be on y-axis, with no loss of generality

Then we have

$$\begin{aligned} P &= V - bj \\ T\cdot P &= T\cdot k = H\cdot V = H\cdot P = 0 \\ V &= \sin\Delta\lambda \cos\phi\, i + \cos\Delta\lambda \cos\phi\, j + \sin\phi\, k \end{aligned}$$

where i, j, and k are the usual rectangular unit vectors and b (= 6.62) is the ratio of the satellite distance from the center of the earth to the radius of the earth.

Hence

$$H\cdot P = H\cdot V - bH_y = -bH_y = 0$$

Thus $H_y = 0$ and H lies in the x-z plane.

Define a_H such that $H = \sin a_H i + \cos a_H k$. Then

$$H\cdot P = \sin a_H \sin\Delta\lambda \cos\phi + \cos a_H \sin\phi = 0$$

$$\tan a_H = -\tan\phi/(\sin\Delta\lambda) \qquad (1)$$

Because of $T\cdot k = 0$, we have $T_z = 0$ and T lies in the x-y plane.

Define a_T such that $T = \sin a_T i + \cos a_T j$. Then

$$T\cdot P = \sin a_T \sin\Delta\lambda\cos\phi + \cos a_T(\cos\Delta\lambda\cos\phi - b) = 0$$

$$\tan a_T = (b - \cos\theta)/(\sin\Delta\lambda\cos\phi) \qquad (2)$$

where θ is defined such that $\cos\theta = \cos\Delta\lambda\cos\phi$.

Let θ_p be the angle between T and H. Then

$$\begin{aligned} \cos\theta_p &= T\cdot H = \sin a_T \sin a_H \\ \tan\theta_p &= \sqrt{1 - \sin^2 a_T \sin^2 a_H}/\sin a_T \sin a_H \\ \tan\theta_p &= \sqrt{1 + \tan^2 a_T + \tan^2 a_H}/(\tan a_T \tan a_H) \qquad (3) \end{aligned}$$

Finally, by substituting (1) and (2) into (3), one obtains after some manipulations

$$\tan\theta_p = -(\sin\Delta\lambda/\tan\phi)\sqrt{1 + [\sin\theta/(b - \cos\theta)]^2}$$

where the negative sign arises from my choice of positive direction for the angle $\Delta\lambda$.

ORI, Inc.
1400 Spring Street
Silver Spring, Maryland 20910

Telephone: (301) 588-6180

May 6, 1980

Mr. Howard Weinberger
Hughes Aircraft Company
Space and Communication Group
Bldg. 373/B332
Box 919
Los Angeles, Cal. 90009

Dear Howard:

The following comments on your paper "Communication Capacity of the Geostationary Satellite Orbit" are made at your request. They include some subjective evaluations and are offered in light of my previous experiences with papers of a similar nature. But they should be taken as no more than suggestions that are hoped to be helpful in promoting the US interests.

I believe that, in the international arena, the paper will be criticized on two levels: Many of the assumptions on which the results are based will be attacked as being unsupported, unrealistic, and overly optimistic; and the overall purpose of the paper will be misinterpreted as being political rather than technical. I will address both these issues.

As to the overall impression that the paper tend to produce, I believe most misinterpretations can be avoided simply be leaving out all vague and subjective statements and restricting the text to factual matters. For example: "It will be shown that the capacity ... greatly exceeds any likely demands ... " In fact, no such thing is shown since the likely demand is not discussed (not even by reference), except for the footnote on pg. 5, and even there nothing is said about likelihood of demand. Furthermore, demand is highly nonuniform geographically, and average overall capacity may not be relevant. Other examples are use of the words "extremely large", "appears adequate", etc.

As to specific points, the following come to mind:

1. Assumption of homogeneous coverage areas. This is not realistic. If large and small coverage areas coexist, the satellite antenna discrimination is determined by the largest ones.

2. Uniform satellite spacing. This brings to mind a priori planning. For nonhomogeneous systems, uniform spacing is neither optimum nor desirable.

3. Numbers used for isolation. It is not clearly stated how they were obtained, and they seem high. For crosspolarization, 33 dB is right for the satellite antenna, but how much it is for the ground antenna? If it is less than that, the lesser number would

prevail. How was 32.5 dB obtained for the ground antenna discrimination? I get 29.3 dB for a 5 m antenna at 4 GHz at 5°.

4. Single entry vs. total interference. This question must be discussed in much greater detail. In an intensively populated environment (many frequency reuses), the potential number of entries is very large, even if ocean areas are excluded.

5. Reduction of total interference by 5 dB. This does not seem realistic. The absence of beams to cover the oceans is no help to interior beams surrounded by a large number of other beams, all covering land areas.

6. Loading. A value of C/I of 23 dB and a resulting value of 1500 pWp0 implies a loading of less than 650 voice channels in a 36 MHz transponder. This is less than the 750 voice channels used in Table 3, and much less than may be economically acceptable to the users.

7. Visible area. The area visible from a given orbit position, or rather the area that can usefully be served, depends on the elevation angle. Even for zero degrees elevation angle, only 85% of half the earth's surface is usable. This shrinks to 74%, 68%, and 60% for elevation angles of 5°, 10°, and 15°, respectively.

8. Effect of latitude and size of a service area on service arc. Because of this, the number of frequency reuses possible in any one service area will vary widely with location and sizes of service areas. Thus the distribution of frequency reuses will be far from uniform, and there will not, in general, be any correlation between distribution of requirements and distribution of capacity. It may well be that, in a small country near the equator, the capacity will be very large. But that is no help to a large country at high latitudes whose requirements are very large.

These points are not exhaustive, nor are they all of equal importance. Some of them you have addressed already in Section 7 of your paper. But I believe that the emphasis in a paper of this type should be in using only conservative and well supported assumptions that cannot be attacked easily. When speculation about the future is involved, this should be cleraly stated and, if possible, supported by references.

I would also like to mention that the paper as it stands could be used as an argument <u>for</u> a priori planning in two ways. Firstly the advocates of planning could say: "If the capacity is as big as all that, then what are you worrying about? Why not assign enough frequencies and orbit positions to us who want them? There will be more than enough left over for you to use as you please." And the second argument could run as follows: "The high capacity that you predict is based on uniform spacing, uniform coverage, homogeneous systems, etc. - all conditions that are best achieved with a priori planning. Without this planning, the capacity may be greatly reduced. So, to assure yourself and us of the benefits of this huge capacity, a priori planning is clearly a necessity." I don't know if a paper on capacity can ever be written so as to avoid these arguments entirely, but I think an effort in this direction can be made by deemphasizing the capacity estimates based on idealized assumptions and by emphasizing the reductions in capacity that will result from more realistic assumptions.

I hope all this will be helpful to you.

Sincerely yours,

Peter H. Sawitz

Peter H. Sawitz

cc: Dick Parlow, NTIA
Harry NG, NTIA
Jim Potts, COMSAT

ORI, Inc.
1400 Spring Street, Silver Spring, Maryland 20910
(301) 588-6180